CLINICAL OUTCOMES AFTER LUMBAR SURGERY AUGMENTED WITH DIAM INTERSPINOUS IMPLANT

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ABSTRACT

Background

The Device for Intervertebral Assisted Motion (DIAM^{TM}; Medtronic Sofamor Danek, Memphis, USA) is an interspinous implant employed in the surgical treatment of lumbar degenerative disease. Its purported effect is a relative segmental kyphosis imposed via distraction of the posterior elements, which is believed to reduce pain-generating neural tissue compression or encroachment, while providing limitation to lumbar extension. Published evidence for the DIAM's clinical and biomechanical efficacy is limited and generally based on year-long retrospective studies that do not reference standardised or recommended outcome instruments or thresholds defining an acceptable response. The DIAM is applied to cases with wide clinical indications that encompass various diagnostic groups. It may be implanted as an isolated procedure but is typically used to augment other lumbar surgeries, the most common being lumbar decompression. Existing evidence for the DIAM reports a promising influence on pain, function and satisfaction in the short term. However, little evidence examines the relationship between subjective postoperative improvement as determined by the patient, and objective measures in vivo of its biomechanical effect on spinal curvature.

Purpose

The primary aim of this thesis investigation was to examine the effect of the DIAM on patient-reported pain and function over a two year postoperative course and compared with defined recommendations for minimal clinical important differences (MID). The purported biomechanical effect of DIAM surgery was assessed in vivo by examining serial change in spinal posture from subjects' skin surface using video rasterstereography, and radiographic vertebral alignment, over the postoperative period and compared to preoperative baseline. Interactions between subjective patient-reported pain and function, and objective measurements of spinal curvature were explored in order to better define clinical indications and prognostic determinants for successful use of the DIAM in the surgical treatment of lumbar spine disease.

Methods

This investigation comprised two main phases of an observational longitudinal design that followed separate cohorts of DIAM surgery cases sourced from a single-surgeon neurosurgical practise in Perth, Western Australia. First, a retrospective audit of patient-reported outcomes data, collected prospectively over a two year period from a consecutive series of 39 cases [21 females, 18 males; mean age 51 yrs], acted as a hypothesis generator for the second phase of the

study. The prospective study assessed 81 cases [37 females, 44 males; mean age 52 yrs] who received DIAM-inclusive lumbar surgery from the same surgeon. The prospective arm of the study involved serial assessment of three main clinical outcomes: (i) Patient-reported health related quality of life (HRQoL) as determined using a standardised questionnaire with an emphasis on response in terms of back pain, leg pain [visual analogue scales (VAS)] and function [Oswestry Disability Index (ODI)] and including patient satisfaction with symptoms and medication use; (ii) Surface-derived sagittal thoracolumbar spinal posture [lumbar lordosis (surface LL), lumbar depth (LD), pelvic incidence (PI), thoracic kyphosis (TK), and thoracolumbar sagittal balance (GSB)] as determined using video rasterstereography; and (iii) Skeletal lumbar spinal alignment [lumbar lordosis (skeletal LL), sacral inclination (SI), primary disc angle (PDA), supradjacent disc angle (SDA), lumbar sagittal balance (RSB), and regional and local radius of curvature (RoC)] as measured from digital standing plain radiographs. Surgical subjects were variously classified according to demographic, anatomical, diagnostic and surgery-related categories in order to apply multiple sub-set analyses aimed at identifying prognostic determinants of response over two years. As a comparator for the surgery cases, surface spinal posture in eleven healthy volunteers was assessed over a two year period of observation.

Outcomes were assessed at pre-determined time-points along the two-year postoperative course in order to identify any critical stage in patients' postoperative response to the surgery. All 81 cases were assessed for their HRQoL at seven time-points: preoperative baseline, 6 weeks, 3, 6, 12, 18 and 24 months postoperatively. Surface thoracolumbar posture was measured via video rasterstereography in 39 cases from the main cohort [17 females, 22 males; 54yrs] at baseline and six weeks after surgery, with serial assessment in the first postoperative year [baseline, 6 weeks, 6 and 12 months] available for 27 cases [13 females, 14 males; 55yrs]. Skeletal lumbar alignment was measured using erect lateral radiography in 59 cases [25 females, 34 males; 52yrs] at baseline and six weeks after surgery, with serial assessment in the first postoperative year [baseline, 6 weeks, 12 months] available for 40 cases [20 females, 20 males; 55 yrs].

Interactions between outcomes were assessed in terms of baseline values, serial response to the surgery and according to demographic, anatomical, diagnostic and surgical procedural-based sub-groups. Responder groups were defined for back pain, leg pain and function achieved at one or two years after surgery compared to their preoperative baseline. Moderate responders had 30% or more improvement in pain and function, a minimal responder described 20-29% and 15-29% improvement in pain and function, respectively, while non-responders were cases reporting anything less than a minimal response (<20% pain, <15% function) to the surgery.

Results

Minimal clinical improvement in back and leg pain and function were shown at all time-points to 24 months compared to preoperative baseline ($p<0.0001$). The greatest improvement occurred by the 6 week and 3 month postoperative points for pain (back and leg) and function, respectively [back pain by 30.5%, leg pain by 29.3%, function by 18.7%; $p<0.0001$] however they gradually deteriorated out to two years after surgery despite remaining significantly better than preoperative values. Approximately four in five patients had an improved response at one year postoperatively, while half the subjects were responders at two years. The proportion of subjects satisfied with their symptoms was similar at 12 [back=48 of 81, leg=44 of 74, function=48 of 81] and 24 months [back=46 of 81, leg=42 of 74, function=47 of 81]. No significant difference in postoperative response was noted between cases with primary disc versus zygapophysial joint pathologies, despite an initial indication that the latter would respond better. Sub-group analyses showed superior improvement in subjects diagnosed with foraminal stenosis at one (improved by: back=32%, leg=40%, function=22%; $p<0.0001$) and two years (improved by: back=29%, leg=38%, function=22%; $p<0.0001$) postoperatively. Cases with degenerative spondylolisthesis had the worst response in self-reported pain and function compared to other diagnostic groups ($p<0.05$). Cases receiving more than one adjunctive decompression procedure had a better response in back and leg pain at one year (improved by: back=32%, leg=33%; $p<0.05$) and leg pain at two years (improved by: leg=30%; $p<0.05$) than those receiving a single decompression technique [1 year: back=19%, leg=16%; 2years leg=9%] in addition to their DIAM.

No change to any variable for surface thoracolumbar curvature was present at the first and second postoperative years compared to baseline. No change to skeletal lumbar curvature was shown at one year after surgery compared to baseline. LD, as determined from the skin surface via rasterstereography, reduced in the early 6 week postoperative period [-4.8mm; $p<0.001$]. A small reduction was noted in PDA [-2.2˚; $p<0.01$] by 6 weeks after surgery as measured from standing lateral radiographs. Both surface LD and skeletal PDA reverted back to baseline values by one year. No strong associations between subjectively reported pain and function and objective measures of spinal curvature were shown. Normalised to baseline back pain responders showed an early thoracolumbar postural straightening, which differed from non-responders ($p<0.05$) whose thoracic and lumbar curvatures subtly increased. Non-responders in terms of absolute back pain and function were cases with negative skeletal lumbar sagittal balance preoperatively [in terms of: back=-8.7 (method-relative millimetres [Rmm], function=-5.3Rmm], while moderate responders had a positive RSB [in terms of: back=13.0Rmm, function=22.4Rmm; $p<0.05$]. Non-responders showed more early (6 weeks) flattening at the primary disc angle compared to moderate responders [in terms of: back=-3.9˚ vs. -1.0 ($p<0.01$);

function=-3.5˚ vs. -1.2˚ ($p<0.05$)].

Conclusions

Lumbar surgery augmented with a DIAM interspinous device resulted in minimally acceptable improvement in back and leg pain and function at all time-points to 24 months compared to preoperative baseline. However, improvement did not represent a clinically meaningful or important change for the group of 81 cases assessed, where responder numbers declined between 1 and 2 years. Peak improvement occurred by 3 months and subsequently showed gradual deterioration. Cases diagnosed with foraminal stenosis and those receiving more than one adjunctive decompression procedure responded best. Degenerative spondylolisthesis cases did not improve. Appreciable flattening in the depth of the surface lumbar contour was present in the early postoperative period, as was a subtle relative kyphosis at the primary index segment. Both LD and PDA reverted back to baseline values by 6 and 12 months, respectively.

Results of the present study must be considered cautiously with respect to the heterogeneous, highly selected cohort. The investigation has provided insight toward defining clinical indications for DIAM-augmented surgery, wherein FS cases responded best and DS cases least. Early (6 weeks) postoperative postural alteration and change to index segment angulation may reflect patient response in the longer term (1-2years). This study provides a basis for further investigation to refine clinical guidelines for DIAM-augmented surgery in managing lumbar pathology.

STATEMENT OF ORIGINALITY

This thesis is presented for the degree of Doctor of Philosophy at The University of Western Australia, through the Centre for Musculoskeletal Studies, School of Surgery.

The research project was developed by the author, in consultation with supervisors, Winthrop Professor Kevin Singer, Director of the Centre for Musculoskeletal Studies, School of Surgery, The University of Western Australia; Dr Roger Price, Head of Department, Medical Technology and Physics, Sir Charles Gairdner Hospital, and Adjunct Associate Professor, School of Physics, The University of Western Australia; and Mr. Quentin Malone FRACS, Neurosurgeon, Centre for Neurological Surgery, Perth, Western Australia, who have also been involved in editing of this thesis.

The recruitment of volunteers, the planning, and management of this study, were the sole responsibility of the author. Surgical patients were recruited under direction from Mr. Quentin Malone and according to University informed consent ethical standards. The author conducted all aspects of testing required for this research project, with the exception of spinal radiology. The author independently analysed the data in consultation with her supervisors.

The material comprising this thesis is the original work of the author towards the PhD degree, unless otherwise stated. This thesis has not been submitted, either in part or whole, for the award of any other degree at this or any other University.

Rebecca Crawford

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PREFACE

Ethics

Approval to conduct the studies outlined in this thesis was granted by the Human Research and Ethics Committee of The University of Western Australia. Approval documentation is provided in Appendices II.1 & II.2. All neurosurgical patients involved in the study provided written, informed consent after reviewing a plain language description statement (Appendix I.1 & I.2). Consent from the convenience sample of volunteers was obtained and maintained via face-to-face personal communication with the author.

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THESIS PUBLICATIONS

This thesis contains three published, co-authored papers; their chapter location within the text is indicated.

1. Peer reviewed journal papers

Crawford RJ, Price RI, Singer KP. 2009. The effect of interspinous implant surgery on back surface shape and radiographic lumbar curvature. Clinical Biomechanics 24 (6): 467-472. [Chapter 6]

Crawford RJ, Price RI, Malone Q, Singer KP 2009. Clinical outcomes after lumbar surgery augmented with DIAM interspinous implant. Journal of Musculoskeletal Research, 12 (2): 59-69. [Chapter 4]

Crawford RJ, Price RI, Singer KP 2009. Surgical treatment of lumbar segment disease with interspinous implant: review. Journal of Musculoskeletal Research, 12 (3): 153-167. [Chapter 2.6]

2. Poster presentations

Crawford RJ, Price RI, Malone Q, Singer KP. Clinical outcomes at 24 months following lumbar surgery augmented with DIAM interspinous implant. Spine Society of Australia Annual Meeting: Brisbane, April 2009.

Crawford RJ, Price RI, Malone Q, Singer KP 2009. Pain, function and spinal curvature following lumbar surgery augmented with the DIAM interspinous implant. Spine Society of Australia Annual Meeting: Brisbane, April 2009.

DECLARATION FOR THESIS CONTAINING PUBLISHED WORK

As outlined above, this thesis contains published co-authored work comprising Chapters 2.6, 4 and 6. These three papers were published during the course of the thesis investigation in collaboration with supervisors who provided an editorial role in their submission to journals. As such, the work contained within these chapters was by greater majority my own at submission for publication (>75%) with additions to each paper made by myself for thesis inclusion.

Rebecca Crawford	W. Professor Kevin Singer
PhD Candidate	Coordinating Supervisor

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GLOSSARY OF ABBREVIATIONS

ADLs	Activities of daily living
ANOVA	Analysis of variance
AP	Anteroposterior
BMI	Body Mass Index
CV	Coefficient of variation (%CV)
CT	Computed tomography
DIAM	Device for Intervertebral Assisted Motion
DM	Dimple midline (Rasterstereography)
GSB	Global sagittal balance (thoracolumbar surface curvature)
HRQoL	Health Related Quality of Life
IAP	Inferior articular process
IAR	Instantaneous axis of rotation
ILS	Lumbosacral inflexion
ISL	Interspinous ligament
ISP	Interspinous
ITL	Thoracolumbar inflexion
JOA	Japanese Orthopaedic Assessment (HRQoL outcome instrument)
LASD	Lumbar axis sacral distance
LBP	Low back pain
LD	Lumbar depth
LL	Lumbar lordosis
LP	Leg pain
L/S	Lumbar spine
MF	Multifidus
MISS	Minimally Invasive Spinal Surgery

MRI	Magnetic Resonance Imaging
ODI	Oswestry Disability Index
PA	Posteroanterior
PDA	Primary disc angle
PI	Pelvic inclination (surface curvature)
PLC	Posterior ligamentous complex
PSIS	Posterior superior iliac spine
RoC	Radius of curvature
RMDQ	Roland Morris Disability Questionnaire
Rmm	Method-relative millimetres
RSB	Regional sagittal balance (lumbar skeletal curvature)
RTA	Road traffic accident
SAP	Superior articular process
SD	Standard deviation
SDA	Supradjacent disc angle
SI	Sacral inclination (skeletal curvature)
SSL	Supraspinous ligament
SP	Spinous process
SVA	Sagittal vertical axis
TDR	Total disc replacement
TK	Thoracic kyphosis
T/S	Thoracic spine
VAS	Visual analogue scale
VC	Vertebral centroid
VP	Vertebral prominens
X-Stop	X-Stop interspinous device

OPERATIONAL DEFINITIONS

BOX-PLOTS: Box-plots are used throughout this thesis in order to summarise the data in this longitudinal observational cohort study. The standard format uses horizontal lines, which from the top represent the 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles, respectively.

CHANGE SCORES: Change scores for patient-reported back pain, leg pain and function compared to preoperative baseline were employed in two ways in this thesis: time-point value minus the baseline value (e.g. 6weeks minus baseline); and time-point value minus the baseline value, divided by the baseline value. Change scores calculated on the absolute difference between patient-reported values at two time-points were referred to as absolute change [e.g. 12 month value minus baseline value; 12m-B], while change normalised to the baseline value is referred to as normalised change [e.g. absolute change divided by baseline value; (12m-B)/B].

GLOBAL SAGITTAL BALANCE (GSB): This term refers to the measure for thoracolumbar sagittal balance as determined using rasterstereography in assessing surface spinal curvature.

ISP DEVICE GENERATION: Three ‘generations’ of interspinous implants are referred to within the thesis. First generation refers to the earliest reported devices including the novel ‘soft’ device described by Minns & Walsh (1997) and the precursor to the Coflex device, the interspinous U. Second generation refers to the four main implants that represent the next developments, including the DIAM, X-Stop, Wallis and Coflex implants, and for which most ISP literature exists. Third generation refers to the most recent developments of ISP technology where progression to less invasive surgery has seen a move toward unilateral or percutaneous insertion with associated developments in device materials and intrinsic mechanics.

POSTERIOR ELEMENTS: This term is used throughout the thesis to refer to the bony posterior aspects of the vertebral column including the spinous processes, posterior arch (bilateral lamina) and paired facets.

REGIONAL SAGITTAL BALANCE (RSB): This term refers to the measure for lumbar sagittal balance as determined from digital radiographs in assessing skeletal curvature.

RESPONDERS: Responders were identified according to their self-reported improvement in back and/or leg pain and back-specific function as measured with the VAS and ODI outcome tools, respectively, and according to MID recommendations (Dworkin et al. 2008; Ostelo et al. 2008). The terms moderate, minimal and non-responders are employed with reference to the level of response postoperatively. When absolute change scores were analysed, improvement was deemed of moderate clinical importance for function, back and leg pains when 30% or greater reduction in ODI (function) or VAS (back and leg pain) scores occurred. Reductions over 15% for ODI (function) and 20% for VAS (pain) scores represented a minimum acceptable clinical change. Changes less than minimally acceptable were categorised as non-responders. When relative change scores were analysed, improvements in function, back and leg pains that were equal to, or in excess of 20% for VAS or ODI were considered minimally acceptable, while 30% or more improvement was recorded to be of important clinical significance. The values for relative change were based on the lower and upper values described for MID by Ostelo et al (2008). Subjects reporting change in actual or relative pain or function in excess of 50% were considered to have shown substantial improvement.

STATISTICAL SIGNIFICANCE: Statistical significance was defined throughout the thesis with $p<0.05$ representative of a meaningful difference. Specific levels of significance were additionally reported and represented by a coded numeric in Tables, which was modified to a symbol in Figures to avoid confusion with presented case number data. A level of significance of $p<0.05$ is represented by either a ^{1} or *; $p<0.01=^{2}$ or ^; $p<0.001=^{3}$ or ~; and $p<0.0001=^{4}$ or †.

THERAPEUTIC FAILURE: A therapeutic failure has been previously defined in relation to DIAM-augmented surgery as requiring repeat surgery at the initial site of the DIAM implant (Taylor et al. 2007); this definition is employed for this study.

These definitions are presented together here for ease of reference. Methodological aspects will occur again within the relevant text.

CHAPTER 1

Introduction

Low back pain (LBP) is the most widespread and costly musculoskeletal condition in Australia with a point prevalence of 5 million sufferers nationally (AIHW 2000). Treatments for LBP cost AUD$1 billion annually (Walker 2000), with the indirect financial burden being estimated at $8 billion per year, a concerning economic toll (Walker et al. 2003). LBP is the most common health disorder causing labour-force absence in those over 45 years of age (Schofield et al. 2008). Recent prognostic evidence suggests a slow recovery that extends beyond 12 months in a third of Australian patients (Henschke et al. 2008). Feelings of depression and perceived risk of persistence are characteristics most closely associated with poor prognosis. Other independent factors contributing to delayed or reduced outcomes are compensation cases, longer episode duration, older age, high pain intensity, and more days of reduced activity (Henschke et al. 2008).

An 85% lifetime, and 35% point prevalence for low back pain links Australia with other western societies (van Tulder et al. 1995; Frymoyer and Durret 1997; Andersson 1999; Maniadakis and Gray 2000; Walker et al. 2003), where the mounting cost of treatment to the community increases directly with condition chronicity (van Tulder et al. 1995; Frymoyer and Durret 1997; Nachemson 1999; Maniadakis and Gray 2000). Most patients with acute low back pain improve substantially over the first month, however in a minority, pain is persistent and disabling (Pengel et al. 2003). Physical function is worse in people with spinal disorders than in the general population, or in those with most other disease conditions (Fanuele et al. 2000). In America, 5% of people with back pain-related disability, account for 75% of societies' low back pain costs (Frymoyer and Cats-Baril 1991). Early identification of causality, improved outcome prediction and timely application of appropriate treatment and management protocols, has become increasingly important in reducing the economic burden (McIntosh et al. 2000; WHO 2005). A global challenge exists to provide superior intervention both in identifying and managing sub-groups of those with low back pain.

Pain at a symptomatic lumbar motion segment has the potential to originate from the vertebral end-plates, the disc anulus, vertebral periosteum, facet joints, and/or surrounding soft tissue structures (Bogduk 1983). Back pain is frequently attributed to the intervertebral disc, either directly or indirectly (Gunzburg and Hutton 1991; van Tulder 2000). Internal disc disruption that potentially leads to degeneration and/or herniation, are processes that may occur due to acute injury, gradual repetitive minor trauma or aging (Urban and Roberts 2003). Disc disease often compromises the function of the zygapophysial joints, and commonly results in abnormal loading patterns and consequent segmental instability (Butler et al. 1990; Panjabi 2003). Whether disc or facet degeneration precedes each other in the development of lumbar pathology is strongly debated in the literature (Butler et al. 1990; Fujiwara et al. 1999). It is well established that both can independently or in combination result in a painful lumbar spine. However, the specific source of pain continues to dominate contemporary discussion, with methods for identifying its anatomical origins still unclear (Waddell et al. 1992; Chou et al. 2009c; Deyo and Mirza 2009). Poor understanding exists as to whether abnormal segmental motion or abnormal load transmission predominate the cause of back symptoms.

1.1 The Problem

Current surgical treatment for the painful lumbar motion segment is considered imperfect (Nockels 2005; Gibson and Waddell 2007b; Deyo and Mirza 2009). Operative intervention is typically only considered appropriate when nonoperative alternatives have been exhausted, and symptoms have progressed to chronicity (Andersson 1997). Despite back pain and associated radicular pain being reported as the third-ranked reason for surgery in the USA, only 10-15% of cases cannot be treated non-operatively and consequently progress to surgery (Frymoyer and Durret 1997). Australian data suggest that 16,680 lumbar back pain patients per year fail conservative management and therefore represent cases that might be deemed appropriate for surgical intervention (MSAC 2008). This reflects less than 1% of the total Australian population (ABS 2010), not all of whom reach a surgical end point.

Rigid spinal fusion has been the traditional surgical approach for lumbar degenerative and instability conditions. This has been based on the premise that abnormal motion is the primary pathomechanical basis (Gibson et al. 1999; Deyo et al. 2004). Advances in fusion techniques have increased rates of arthrodesis (Martin et al. 2009; Deyo et al. 2010), although a corresponding improvement in pain relief has not occurred (Boos and Webb 1997; Deyo and Mirza 2009). Decompression of lumbar spinal stenosis (LSS) in particular, has experienced the fastest growth (Deyo et al. 2005), although a small decline in surgical procedures for LSS in America was recently reported (Deyo et al. 2010). Increased surgery for LSS has lead to an older cohort with comorbidities undergoing surgery (Deyo et al. 2010). As such, surgical risk may be higher (Cloyd et al. 2008; Martin et al. 2009). Consequently, research and development efforts have focused on alternative technologies aimed at unloading the spinal segment, without losing motion, and employing less invasive surgeries that necessitate limited operative and hospitalisation times (Deyo et al. 2004; Carragee 2006; Deyo and Mirza 2009).

Dynamic stabilisation systems, including the interspinous implant (ISP), have arisen from this endeavour (Minns and Walsh 1997; Bono and Vaccaro 2007; Khoueir et al. 2007). They represent a more cost-effective intervention in Australia when compared with rigid instrumented fusion (MSAC 2008). Post-discectomy mechanical back pain secondary to same-level degeneration is not uncommon and results in substantial health care costs (Parker et al. 2010). The adverse mechanical impact of surgical fusion and/or decompression on adjacent segments and thoracolumbar alignment (Deyo et al. 2004) is thought to be avoided with these dynamic motion-restoring devices (Schmoelz et al. 2003; Korovessis et al. 2004). Spinal stenosis, nerve root compression, segment degeneration and subsequent instability are conditions now being surgically treated with isolated or adjunctive ISP (Khoueir et al. 2007; MSAC 2008; Crawford et al. 2009c). Lumbar surgery with ISP is reported to have a higher financial impact per person than decompression surgery alone (MSAC 2008). This is despite the purported advantage of their minimally invasive surgery, which is promoted to reduce patients' post-operative recovery time and lessen exposure to complications when compared to laminectomy (Hannibal et al. 2006).

Despite an apparent widespread use of ISP devices in the treatment of lumbar spinal disease, limited evidence reports their clinical efficacy and consequently their use may be considered controversial. Review papers have indicated a need for further investigation to define more specifically their clinical indications, particularly when assessed in controlled comparison with other more traditional decompressive and fusion surgeries (Christie et al. 2005; Bono and Vaccaro 2007; Khoueir et al. 2007; Crawford et al. 2009c). One interspinous device has been shown to be more effective that non-surgical therapy for LSS, however the results are only applicable to patients with single or double-level disease, and symptoms relieved by lumbar flexion (Zucherman et al. 2005a; Anderson et al. 2006; Hsu et al. 2006). A criticism of existing investigations describing the utility of ISP implants is their either being funded by the manufacturer of the device, or involving a developer as a leading author (Anderson et al. 2006; Hsu et al. 2006; Senegas et al. 2007; Siddiqui et al. 2007; Taylor et al. 2007; Zucherman et al. 2008).

The investigation presented here sought to focus on lumbar surgery involving one type of interspinous implant, the Device for Intervertebral Assisted Motion (DIAM; Medtronic Sofamor Danek). In employing the DIAM in lumbar surgery, designers purport a restoration of physiological alignment through supraspinous ligament distraction (Palmer 2009), in striving for pain reduction and functional improvement (Taylor et al. 2007; Palmer 2009). A careful review of the literature revealed few investigations assessing patient self-reported outcomes together with the assessment of fundamental biomechanical effects in individuals receiving lumbar surgery augmented with DIAM (Crawford et al. 2009c). Similarly, limited research-supported guidelines describing the clinical application of the DIAM device exist.

The primary aim of this study was to contribute to clinical guidelines that inform the management pathway for the use of the DIAM in lumbar spine disease.

1.2 Clinical Significance

In view of the prevalence of low back pain in Western populations, and the mounting economic burden it represents to society, superior methods of classification and treatment of the condition are of international importance. Two key considerations driving aspects of the study of back pain appear to be: the efficacy of surgery versus the natural history of the disorder, and refining indications for surgery in the absence of serious life or neurological compromise. The question of whether back pain itself represents an indication for surgery is relevant. Surgical interventions for lumbar spine disease continue to be developed in order to provide the least invasive operative alternative for the small proportion of cases that experience persistent symptoms.

ISP implants represent a non-fusion surgical alternative aimed at motion preservation and posterior dynamic stabilisation in the lumbar spine (Crawford et al. 2009c). They may be employed in isolation or more typically as an adjunct to various decompressive techniques in the treatment of degenerative lumbar disease. Successful outcomes are reportedly dependent on appropriate patient selection (Yue and Lawrence 2008) yet limited clinical guidelines exist. These devices were initially developed and widely used in Europe, with several countries allowing their use based on formative evidence of acceptable safety and material property testing (Bono and Vaccaro 2007). Initial verification for improved clinical outcomes is claimed to be encouraging, although the scientific rigour and length of follow-up of supportive investigations has been criticised (Khuoeir et al. 2007, Crawford et al. 2009c). Skepticism of ISP technologies therefore exists for some surgeons who encourage further research (Fehlings and Chua 2010). Several ISP devices are currently the subjects of extensive clinical trials in the USA, while in Australia their continued acceptance is dependent on an improved evidence base (MSAC 2008).

The DIAM is one ISP device used by some Australian surgeons. Clearly defined clinical pathways are not yet established for the use of this surgical system. Knowledge of its purported mechanical effects is generally based on cadaveric studies with a limited analysis on spinal curvature applied in vivo. The present investigation aimed to contribute to the literature discussing clinical outcomes after surgery augmented with the DIAM where subjects studied were sourced from a single-surgeon private practice. Several study design issues were imposed by the referring surgeon, mandating a longitudinal observational design rather than the preferred two-arm cohort study or randomised controlled trial. Limitations arising from the study design are elaborated throughout the thesis. Serial assessment spanned two years and integrated the evaluation of commonly reported outcomes including patient-reported pain and function, and lumbar skeletal parameters based on plain radiographic imaging.

In addition, surface thoracolumbar shape and posture, which is less commonly reported in spinal surgery and in relation to interspinous implants in particular, are assessed.

1.3 Presentation of the Thesis

This thesis is presented in accordance with guidelines provided by the Graduate Research School of The University of Western Australia and is set out in four sections. Section I provides the descriptive chapters of the study. Section 2 presents chapters detailing the study results. Section 3 provides discussion and summary of the investigation. Section 4 presents the appendices, reference list and supporting documentation. The contents of each of these sections are elaborated below.

<u>Section 1:</u> Chapter 1 provides an introduction to the study with an overview of the background, aims, purposes, structure and clinical significance of the work. Chapter 2 contains a literature review that is presented in three parts: Part I – The lumbar spine and associated degenerative disorders; Part II – Lumbar surgery as is relevant to the surgical treatment of lumbar spine disease with interspinous implant (a published review paper is included); Part III – Outcome measures used in the treatment of lumbar spine disease. Each of these Parts contains subsections that relate to aspects of the overall investigation. In an effort to provide a readable thesis, only relevant literature is reviewed, with every endeavour made to present a concise, accurate and representative view of the current knowledge as it pertains to the investigation. Chapter 3 supplies the methodologies employed to test the study hypotheses, the data collection process and, the statistical analysis procedures pertaining to each investigated clinical outcome.

<u>Section 2:</u> Chapters 4 to 8 present results of the study, which have been separated by themes in order to allow for the two published papers (Chapters 4&6) and those intended for submission (all others). An elaborated description of the literature as it pertains to each separate chapter theme is provided where Chapter 2 has not included adequate detail. A discussion as it relates to the specific chapter results is included for each theme. To follow is a brief description of the content of these five chapters. Chapter 4 presents a paper based on Phase I of the project involving a retrospective audit of prospective outcomes data collected over 2 years, for a series of surgical cases implanted with the DIAM. These patients were sourced from the same neurosurgical practice as used in the main prospective arm (Phase II) of this investigation. This initial aspect of the study enquiry functioned as a hypothesis-generator, which informed further aspects of the research. The subsequent hypotheses have been outlined for Phase II in Chapter 3. Chapter 5 presents aspects of surface curvature in asymptomatic healthy volunteers as a means of providing normative data for comparisons of the surgical cohort. Chapter 6 comprises a methodological paper that compares the skeletal and surface curvature over a short (6 week) time frame of a healthy volunteer cohort and an equivalent number of surgical cases that

received lumbar surgery augmented with the DIAM. The methods described in this paper were further developed and applied to monitor change in both healthy volunteers and a larger cohort of DIAM surgery patients over a 24-month period. Chapters 7, 8 and 9 provide the primary results of Phase II of the investigation where clinical outcomes including: patient-reported quality of life (Chapter 7); surface thoracolumbar contour (Chapter 8); and skeletal lumbar curvature (Chapter 9) are described. Chapter 10 explores the interaction between each of the separate clinical outcomes after DIAM-augmented surgery in treatment of their lumbar spine disease: HRQoL and surface curvature; HRQoL and skeletal curvature; and surface and skeletal curvature.

<u>Section 3:</u> Chapter 11 includes Discussion of the compiled results of the investigation in context with the available literature. Themes for the discussion centre around developing clinical pathways aimed at guiding the use of the DIAM (and potentially other interspinous devices) for the surgical management of disorders of the spine. The serial behaviour of surface and skeletal lumbar curvature in a lumbar surgery cohort as compared with healthy volunteers is discussed. Limitations of the study are addressed in this chapter. Conclusions of the present study are drawn in the final chapter (Chapter 12), which also includes a list of recommendations and directions for future studies.

<u>Section 4:</u> Eleven collateral investigations were undertaken to provide additional background information and data in support of the themes discussed in the main study; these have been included as Appendices (VI.1, VI.2, VII.1, VII.2, VII.3, VIII.1, VIII.2, VIII.3, IX, X, & XI) and are variously cross-referenced within their pertinent chapters. Other supportive materials demonstrating the investigative process have also been included as Appendices (I-V). The full reference list is provided.

CHAPTER 2

Review of Literature

2.1 Introduction

There is extensive literature on back pain from a fundamental and clinical perspective. This thesis examined clinical outcomes in cases following lumbar surgery augmented with the Device for Intervertebral Assisted Motion (DIAM; Medtronic Sofamor Danek, Memphis, USA). As such, the review of literature will focus on aspects relating to this single minimally invasive surgical intervention. Essential information included in this review describes: normal lumbar spine anatomy and associated degenerative conditions (Part I), the development of decompressive surgical procedures with an emphasis on interspinous devices (Part II), and the measurement systems employed by this study to assess clinical outcomes in these low back pain cases over 24 months following surgery (Part III). It is acknowledged that this limited review represents a proportion of the considerable literature encompassing the study of the lumbar spine. Complementary information will also be presented within each chapter of the thesis, in addition to that included as background and discussion for the various cross-referenced Appendices.

Part 1: NORMAL AND DEGENERATIVE ANATOMY OF THE LUMBAR SPINE

2.2 Normal anatomy of the lumbar spine

2.2.1 Introduction

The lumbar spine generally comprises: five vertebral bodies, although variations on this exist for 20% of adults (Hanson et al. 2010); their intervening discs; and respective posterior elements, which collectively form a column that provides structural strength and length to the lower trunk, while permitting multi-planar motion (Taylor and Twomey 1980; Adams et al. 2002). Vertebral bodies (VB) and intervertebral discs (IVD) strongly resist compression and bear axial loads imposed by the upper limbs and trunk (Taylor 1975). The principle plane of motion for the lumbosacral region is flexion-extension (Weinstein et al. 1977). Flexion, extension, bilateral side-flexion and rotational movements increase toward the lowest lumbar segments (Allbrook 1957) and are afforded in various degrees by the joints of the region including those formed between the vertebral bodies (inter-body), and those of the interlocking posterior elements (zygapophysial) (Bogduk 2005). In vivo sagittal motion in the lumbar region is affected by gravity and controlled by muscular effort, in particular from the erector spinae

(Taylor and Twomey 1980). The complete lumbar column, whose curvature is typically concave posteriorly, articulates with the sacrum anteriorly via the adjacent L5/S1 IVD and sacral base, and posteriorly through the L5/S1 facet joints (Adams et al. 2002). For the purposes of this study, the superior endplate of the first sacral vertebra (S1; sacral base) is therefore considered and described as an integral component of the lumbar region. Physiological spinal curvatures occur as a result of the trapezoidal shape of vertebral bodies and their intervening intervertebral discs (Bernhardt and Bridwell 1989; Bogduk 2005). Lumbar lordosis usually begins at L1/2 and gradually increases at each level caudally down to the sacrum (Bernhardt and Bridwell 1989). The mean lumbar lordotic apex is the L3-4 disc (SD 0.5 level) and can range between L2 and L5 (Bernhardt and Bridwell 1989).

The anatomical component of this review is restricted to the vertebral motion segment consisting of two adjacent vertebrae, their intervening intervertebral disc (IVD), associated paired zygapophysial joints, interconnecting ligaments, local intimate musculature and associated joint structures (White and Panjabi 1978) (Figure 2.1). Each of these will be described in relation to their adult form to follow.

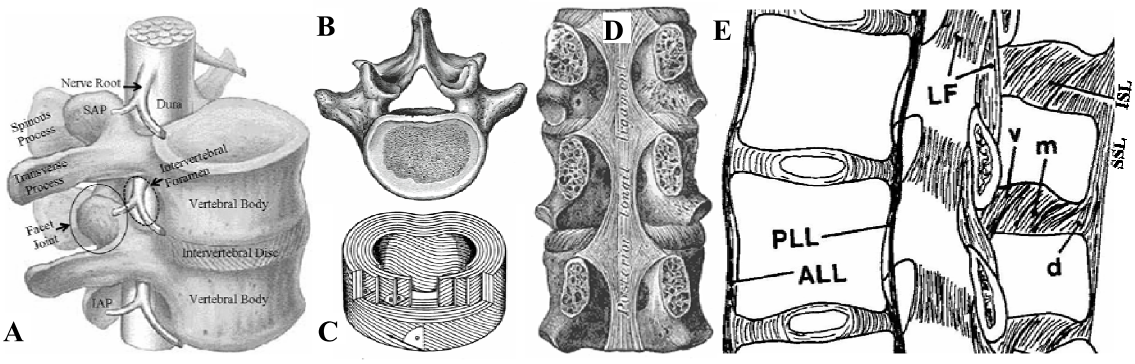


Figure 2.1: Schematic representation of: (A) Lumbar motion segment comprising two adjacent vertebrae, the intervening intervertebral disc, and the unilateral zygapophysial joint, with key vertebral features noted; (B) L5 lumbar vertebra indicating its small spinous process and broad transverse process origin (Warwick and Williams 1980) (Gray's Fig 94); (C) Architecture of the anulus fibrosus (Bogduk, 2005); (D) Posterior longitudinal ligament (Warwick and Williams 1980) (Gray's Fig 302); and (E) interconnecting ligaments: posterior longitudinal (PLL); anterior longitudinal (ALL), ligamentum flavum (LF); interspinous (ISL) comprising ventral (v), middle (m) and dorsal (d) parts; and supraspinous (SSL) (adapted from Bogduk, 2005).

2.2.2 Spinal element classification:

In classifying spinal fractures, Denis (1983) described a three-column theory as a modification of the earlier bi-column classification by Holdsworth to identify the structures contributing to intervertebral stability. The bi-column classification divides the spine into anterior and posterior elements, where all structures anterior to, and inclusive of the posterior longitudinal ligament, is classified as anterior elements (Holdsworth 1963). The anterior longitudinal ligament, the anterior vertebral body and the anterior annulus fibrosus form the anterior column according to Denis (1983). The posterior longitudinal ligament, the posterior annulus fibrosus, and the posterior vertebral body wall form the middle column, while the posterior column constitutes the posterior vertebral arch and the posterior ligamentous complex comprising the supra and interspinous ligaments, zygapophysial joint capsules and the ligamentum flavum (Denis 1983). These two classification systems are illustrated in Figure 2.2. Literature variously uses these classifications to refer to structures comprising the vertebral column. Where reasonable, for the purposes of this thesis, the preferred terminology will reference the three-column classification.

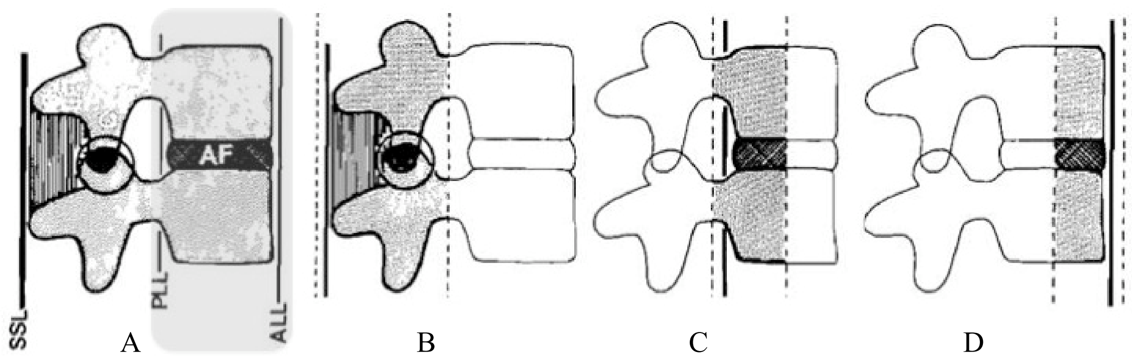


Figure 2.2: The two- and three-column methods of classifying spinal fractures according to Holdsworth (1963) and Denis (1983), respectively. The two-column method (A) distinguishes between anterior (shaded) and posterior spinal structures. The three-column classification defines posterior (B), middle (C) and anterior (D) elements. Figure adapted from Denis (1983).

<u>2.2.3 Lumbar vertebra:</u> Minor differences exist between lumbar vertebrae (Gilad and Nissan 1986; Davies et al. 1989; Panjabi et al. 1992); however a typical lumbar vertebra will be described to outline the normal anatomy. The lumbar vertebral body (VB) is generally large and composed primarily of cancellous bone surrounded by a thin mantle of cortical bone (Twomey et al. 1983). Posteriorly the VB assumes a thicker cortex to support the pedicles and other posterior elements, while its superior and inferior plates are thicker peripherally to accommodate the origin of the anulus fibrosus (Twomey and Taylor 1987). Vertebral bodies are reinforced internally by vertical and horizontal trabeculae, which provide strength for sustaining compressive axial loads that are amplified by muscle contractions in upright postures (White and Panjabi 1978). Posterior wedging of the lowest lumbar vertebra reflects a natural morphological adaptation to compressive load at the apex of lordosis that is concave posteriorly (Farfan 1973; Panjabi et al. 1992).

Bilateral pedicles emerge from the upper VB and are short, thick and horizontal, with a slight lateral inclination. Laminae are broad and descend in an inferomedial direction to lie below the pedicles. The lumbar vertebral canal, bordered by the posterior bony complex and the posterior vertebral body, is triangular with rounded corners, being larger than that found in the thoracic region but smaller than in the cervical spine (Adams et al. 2002). The L1-4 spinous processes

(SP) are thick and broad with a relatively horizontal projection, while the SP of L5 is less substantial (Warwick and Williams 1980). Lumbar transverse processes emerge from the pedicle and are long, thin and compressed in the AP plane with a posterosuperior inclination (Warwick and Williams 1980). The superior articular process (SAP) of the caudal vertebra and the inferior articular process (IAP) of the cephalad vertebra comprise the bony elements of the zygapophysial joint, which will be described later. An example of an L5 vertebra is illustrated in Figure 2.1(B).

2.2.4 Lumbar intervertebral disc (IVD):

IVDs are cartilaginous structures linking adjacent vertebrae that allow for axial load transmission, and controlled mobility into flexion, extension and rotational movements in an otherwise rigid anterior vertebral column (Urban and Roberts 2003). Corresponding to the underlying vertebral body shape, lumbar discs are elliptical across the axial plane (Pooni et al. 1986) and approximately 40mm deep anterior to posterior (Urban and Roberts 2003). Their thickness varies between 7 to 10mm dependent on the individual and segmental level, which occupies approximately one-third of the lumbar region's height (Nachemson et al. 1979; Urban and Roberts 2003). Lumbar discs are the largest in the spine and generally wedge-shaped with increasing cross-sectional area from L1/2 to L5/S1 (Pooni et al. 1986). Lumbar lordosis, developed as a secondary spinal curve early in life as a consequence of upright postures (Lafferty et al. 1977; Ferguson and Steffen 2003), results in the physiological disc wedging with greater anterior compared to posterior disc height (Nachemson et al. 1979; Twomey and Taylor 1987; Urban and Roberts 2003).

Lumbar IVDs are arranged with a central gelatinous nucleus pulposus (NP), surrounded by the concentric lamellae of the anulus fibrosus (AF), and separated from the vertebral bodies (VB) by superior (SEP) and inferior cartilaginous end-plates (IEP) to which the IVD contributes (Taylor 1975; Urban and Roberts 2003). Young and healthy adult IVDs macroscopically display the NP and AF with an indistinct boundary between them (Roberts et al. 2006). Each of the components of the IVD will be elaborated to follow.

Nucleus pulsosus:: The NP is a hydrated gel located in the disc centre that is largely comprised of proteoglycans (50-65%) that function to take in and retain large amounts of water (Taylor 1975; Bogduk 2005). This feature allows for its hydrodynamic properties, which accommodate radial expansion against the anulus and endplates when axially compressed (Buckwalter 1995). The collagen component of the NP is predominantly comprised of collagen Type II fibres that are interspersed throughout its structure (Roberts et al. 2006). The NP and AF function cooperatively to maintain stiffness of the IVD against compressive loading, while allowing sufficient compliance to afford interbody movement (Adams et al. 2002). The NP water content reduces with increasing age (Twomey and Taylor 1987) as a consequence of diminishing proteoglycan size and their inability to aggregate with hyaluronate (Urban and Roberts 2003).

Anulus fibrosus: The AF is composed of laminated fibrocartilage with obliquely oriented, predominantly type I collagen fibres that are angled at 60-70 degrees in relation to the spinal axis (Pooni et al. 1986; Bogduk 2005). The collagen fibres are organised into layers called lamellae, with fibres of successive layers running in alternate directions (Taylor 1975). Anulus fibres are anchored to adjacent vertebrae centrally and peripherally by extensions of trabecular fibres and peripherally by the periosteum and the overlying anterior and posterior longitudinal ligaments (Urban and Winlove 2007). Lamellae in the human lumbar disc have been shown to number 15 to 25 (Marchand and Ahmed 1990), with some layers blending such that not all lamellae complete the disc's circumference (Bogduk 2005). Figure 2.1 (C) illustrates the architecture of the AF. The proportion of incomplete layers increases toward the posterior anulus, with thicker layers anteriorly and laterally, and thinner, more tightly packed layers posteriorly (Bogduk 2005). Inner fibres of the anulus pass into the endplates encompassing the NP, while outer fibres insert as Sharpey's fibres into the outer vertebral rim thereby anchoring the AF and epiphyseal ring together (Roberts et al. 1989; Roberts et al. 1991). Anular fibres become tight and rigid under tension, helping to constrain the healthy nucleus pulposus, particularly in rotation (Farfan 1973; Taylor 1975). The anulus is vascular in infancy, however progresses toward avascularity by adulthood (Twomey and Taylor 1987).

Vertebral end plates: The interfaces between the vertebra and disc junctions are formed by the vertebral end plates comprised of hyaline cartilage that graduates to a more calcified cartilage adjoining the bone (Roberts et al. 2006). End plate thickness is greatest in the lower lumbar vertebrae and varies across the width of the disc to be thinnest centrally (Roberts et al. 1989; Moore 2000). Being between 0.1 to 1.6mm, end plates are considerably thinner than the discs themselves (Roberts et al. 1989; Urban and Roberts 2003). End-plates consist of graduating collagen fibres and proteoglycans, with the highest collagen concentrations covering the anulus, and the highest water and proteoglycan concentrations approximating the nucleus (Roberts et al. 1989). Similarity of the end-plate to the adjoining disc is purported to enable diffusion of small molecules from the vertebral body vessels, via the end-plates, to the NP where vascular contacts are more abundant (Maroudas et al. 1975; Urban et al. 2004; Roberts et al. 2006). This mechanism is considered the disc's principle nutrition source allowing for nutrient dispersal to, and metabolite removal away from the disc (Urban et al. 2004).

2.2.5 Lumbar zygapophysial joints:

The lumbar zygapophysial joints are paired synovial joints that link the vertebral arches of two adjacent vertebrae. Each joint is comprised of a posteromedial-facing superior articular process from the caudal vertebra, and a reciprocal anterolateral-facing inferior articular process from the cephalad vertebra (Taylor and Twomey 1986; Cavanaugh et al. 1996; Dreyer and Dreyfuss 1996). Lumbar facet joints are oriented in the sagittal plane in the upper lumbar spine, and approach a more coronal orientation toward the sacrum (Odgers 1933; Farfan 1978). Wide variation in their course exists between individuals (Cihak 1970), which may be related to the variable development and action of attaching multifidus (Odgers 1933). Facet joints form the posterior border of the intervertebral foramina and contain hyaline cartilage, joint space, intra-articular menisci, synovial membrane, fibrous capsule and nociceptive fibres (Dreyer and Dreyfuss 1996; Adams et al. 2002) that are innervated via the medial branches of the dorsal rami (Bogduk 1983). Synovial folds are a potential pain source if impinged intra-articularly (Giles 1988).

Lumbar facet joints: contribute to spinal stability, provide a mechanism for load transfer, allow for mechanoreception, and limit intervertebral motion, specifically in axial rotation, extension and anteroposterior (AP) translation (Adams and Hutton 1980,1983; Yang and King 1984; Cavanaugh et al. 1996). Yang & King (1984) found that normal facet loads bear up to 25% of attendant body weight, increasing up to 47% in the presence of osteoarthritis. Facet joint forces increase through extension and are minimal in flexion (Nachemson et al. 1979; Adams and Hutton 1980,1983; Dunlop et al. 1984; Cavanaugh et al. 1996), with slight flexion shown to relieve both facet and posterior anulus compression (Adams and Hutton 1981). The inferior margins of the lumbar facet joint are known to bear the greatest resistance in the extended spine (Dolan & Adams, 2001) as the joint moves into its closed packed position to prevent vertebral displacement (Yang and King 1984).

2.2.6 Lumbar ligaments:

The kinematic behaviour of the lumbar motion segments is related in part to the provision of stability via the ligamentous structures that do so by limiting excessive motion (Behrsin and Briggs 1988). These ligaments include the: anterior and posterior longitudinal ligaments; ligamentum flavum; facet capsules; interspinous, supraspinous, intertransversal and iliolumbar ligaments, which are outlined below and illustrated in Figure 2.1 (E). The dimensions of these lumbar ligaments show considerable variability between individuals (Rissanen 1960).

Anterior and posterior longitudinal ligaments: The anterior (ALL) and posterior longitudinal ligaments (PLL) are composed of longitudinal fibres of varying length and thickness that assist in connecting vertebral bodies through the length of the spine (Rissanen 1960). The extensibility of the ALL and PLL decreases rapidly to the 4th decade when the progression of stiffening continues but is less marked (Rissanen 1960). The ALL is said to be the most developed in regions of lordosis including the cervical and lumbar spines (Warwick and Williams 1980;

Bogduk 2005) and is reportedly stronger than the PLL (Rissanen 1960). In the lumbar region, the ALL represents a strong, thickened band that attaches into the anterior margins of the lumbar vertebrae and terminates in a broad attachment onto the pelvic surface of the sacrum (Putz 1992). ALL attachment points are somewhat contentious however the general consensus indicates it has minimal loose attachments to the anulus, with its deepest fibres joining adjacent bones and the superficial fibres spanning over several vertebrae to attach to vertebral edges (Behrsin and Briggs 1988). Adams et al (2002) speculate that many of its fibres constitute tendons of the diaphragm. The PLL attaches posterior vertebral bodies to form the anterior wall of the spinal canal (Behrsin and Briggs 1988; Adams et al. 2002). In the lumbar region it has a saw-tooth appearance where it narrows to pass the vertebral bodies, and flares to partially envelop the posterior IVD wall, leaving the posterolateral disc uncovered (Farfan 1973; Warwick and Williams 1980). The PLL comprises several layers, those deeper bridging uni- or bi-segmentally, and the more superficial ones passing across 3 to 4 vertebral levels (Warwick and Williams 1980; Bogduk 2005). The free surface of the PLL is separated from the duramater by loose areolar tissue, which progresses distally into fibrous bands with more intimate connection (Behrsin and Briggs 1988).

Ligamentum flavum: The intervals between the laminae of adjacent vertebrae are filled by the ligamentum flava (LF), which are so named due to their yellowish colour as a consequence of comprising predominantly elastic tissue (Brash 1951; Nachemson and Evans 1968). The LF attaches to the front of the lower border of the upper lamina, and below to the back of the upper border of the succeeding lamina, providing closure between them (Yong-Hing et al. 1976). Each vertebral interval comprises a left and right ligamentum flavum, which are narrowly separated centrally to allow for vascular interconnections (Yong-Hing et al. 1976). Laterally they extend to the facet joints, forming the medial facet joint capsule (Putz 1992). Elasticity of healthy ligamentum flavum permits separation of the lamina during flexion, while not folding to compromise the dura or inter-lamina or foraminal region during extension (Yong-Hing et al. 1976; Adams et al. 2002). Additionally, the LF functions to protect neural tissues from their approximating osseous structures (Behrsin and Briggs 1988; Putz 1992).

Facet joint capsule: The zygapophysial joint is synovial and its capsule is generally described as thin and loosely attached between engaging SAPs and IAPs (Adams et al. 2002). Short, tight, fibrous fibres are reported posteriorly to run transversely, while longitudinally the capsule is believed to be more lax to accommodate sagittal plane motion (Adams et al. 2002). Authors have reported it to be reinforced posteriorly by multifidus, inferiorly by the interspinous ligament and replaced anteriorly by the ligamentum flavum (Yong-Hing et al. 1976; Putz 1992; Bogduk 2005). In flexion, the capsule is considered the major stabilising structure capable of resisting in the region of 50% of the full flexion force (Adams et al. 1980; Posner et al. 1982;

Adams and Hutton 1983).

Interspinous ligament: The interspinous ligaments (ISL) of the lumbar region are purported to be the most strongly developed in the spine (Putz 1992). Anterior, middle and posterior collagen fibres comprising the ligament are generally found to orientate in a posterosuperior direction in connecting the lower border of the spinous process of the cephalad vertebra, with the upper border of the spinous process of the caudal vertebra (Rissanen 1960; Heylings 1978; Bogduk 2005). ISL fibre orientation is reported differently in anatomical texts (Brash 1951; Warwick and Williams 1980) however agreement in later literature exists. Anterior attachments begin bilateral then merge posteriorly toward the deep supraspinous ligament fibres (Behrsin and Briggs 1988). Complementary connections to the thoracolumbar fascia posteriorly and the adjacent facet joint capsules and ligamentum flavum anteriorly add to the tensile integrity of the ISL (Aspden et al. 1987; Johnson and Zhang 2002). Believed to act as a guide during flexion in the sagittal plane, the fibres of the lumbar interspinous ligaments become increasingly tensioned with forward bending (Heylings 1978; Hindle et al. 1990), which contributes to counter the accompanying shear stress during this movement (Putz 1992).

Supraspinous ligament: The supraspinous ligament (SSL) extends the length of the vertebral column, approximating the superficial fibres of the interspinous ligaments and deep fibres of the thoracolumbar fascia (Putz 1992). Authors appear divided in terms of its structure, with early literature indicating a distinct and separate ligamentous entity (Warwick and Williams 1980), while others assert its composition to be tendinous fibres of various myofascial structures, particularly the longissimus thoracis and lumbar multifidus muscles, and the posterior layer of the thoracolumbar fascia (Adams et al. 2002; Johnson and Zhang 2002; Bogduk 2005). While considered a distinct structure formed by these contributing tissues in the upper lumbar spine, the SSL blends with neighbouring myofascia below L3 (Behrsin and Briggs 1988; Putz 1992). At L5 the posterior layer of the thoracolumbar fascia merges with the common erector spinae aponeurosis to attach to the spinous process (Johnson and Zhang 2002). Tendinous origins of multifidus and the aponeurosis of erector spinae contribute to the dense midline connective tissues toward S3, and diminish caudally to be absent at the coccyx (Johnson and Zhang 2002).

The SSL is believed to afford tensile strength particularly in sagittal-plane flexion as a complement to other posterior ligamentous structures (Putz 1992; Heuer et al. 2007). Absence of the SLL in the lower lumbar levels provides a potential explanation for the increased flexion reported toward the lumbosacral junction (Bogduk 2005). Histological study has indicated potential for the SSL to be ossified in some cases (Rissanen 1960).

The supraspinous and interspinous ligaments account for less than 20% of the overall bending moment of the motion segment, with their action only occurring in late flexion and rapidly escalating towards full range (Adams et al. 1980; Hindle et al. 1990). These ligaments are thought to provide useful yet minimal assistance to the posterior thoracolumbar myofascial tissues in restraining passive flexion and in isolation during lifting are shown to have little mechanical function (Hindle et al. 1990). Stretch stimulation of the SSL results in local and bilateral multifidus activation, which Holm et al. (2002) speculates supports its stabilising role (Holm et al. 2002).

Intertransverse ligaments: Disagreement exists in the literature regarding intertransverse ligaments, with descriptions varying between insubstantial membranes of collagen fibres, to well-developed bands that connect the lumbar transverse processes (Behrsin and Briggs 1988; Heuer et al. 2007). Authors agree on their role in separating anterior and posterior myofascial compartments (Behrsin and Briggs 1988; Adams et al. 2002; Heuer et al. 2007).

2.2.7 Muscles of the lumbar region:

Muscles are the principle tissues surrounding the vertebral column and can be divided into three groups: the anterolateral, intertransverse and posterior muscles (Adams et al. 2002). The erector spinae, abdominal, and psoas muscles all contribute to the functional stability of the lumbar spine (Panjabi 1992) however only those existing dorsally will be outlined in this review, with specific reference to: interspinales, multifidus, longissimus thoracis, and iliocostalis lumborum muscles, particularly as they relate to the spinous processes and associated ligaments. Schematic representation of these muscles has been provided in Figure 2.3.

Multisegmental muscles are reported to be more efficient in stabilising the spine in the frontal plane than those with single intersegmental attachments (Crisco and Panjabi 1991). Under static body-weight, intervertebral instability exists in motion segments resected of their musculature unless intervertebral stiffness is not otherwise increased or replaced (Crisco and Panjabi 1991; Heuer et al. 2007). Muscles originating from the pelvis rather than those that are intersegmental, are said to more efficiently facilitate increased spinal loading (Crisco and Panjabi 1991). Studies report smaller paraspinal muscles, particularly multifidus, in the presence of acute and chronic bilateral or ipsilateral low back pain (Cooper et al. 1992; Hides et al. 1994; Danneels et al. 2000; Zhao et al. 2000; Hodges et al. 2006), while others report no association (Kalichman et al. 2010).

An indirect relationship between multifidus-erector spinae density and ipsilateral segmental facet joint osteoarthritis has been shown, as well as associations between multifidus density and spondylolisthesis, and erector spinae density and intervertebral disc narrowing (Kalichman et al. 2010). Type I fibres (slow-twitch) on the diseased side have been shown to be smaller in patients reporting central low back pain (Zhao et al. 2000).

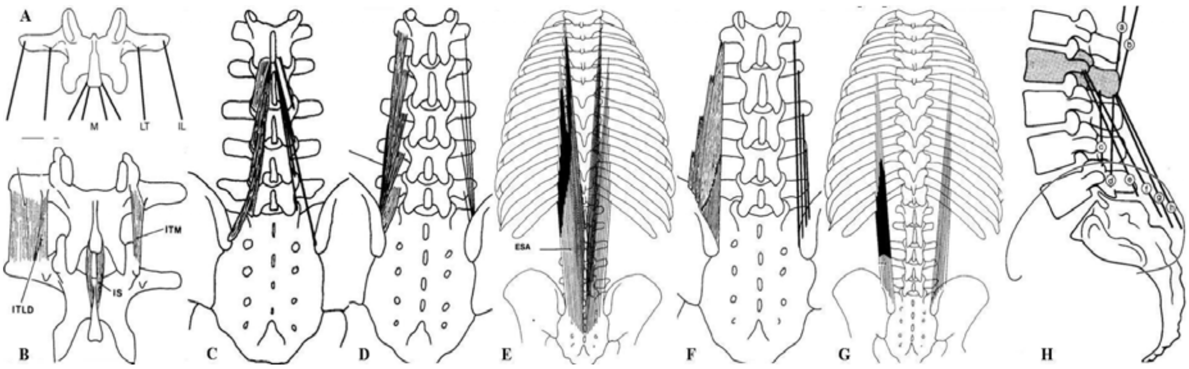


Figure 2.3: Schematic representation of the posterior back muscles. (A) Systematic vertebral attachments and orientation of the iliocostalis lumborum (IL), longissimus thoracis (LT) and multifidus (M). (B) Interspinales (ILS), Intertransversarii laterals dorsales (ITLD), Intertransversarii laterals mediales (ITM). (C) Multifidus fascicles originating at L1. (D) Longissimus thoracis pars lumborum. (E) Longissimus thoracis pars thoracis. (F) Iliocostalis lumborum pars lumborum. (G) Iliocostalis lumborum pars thoracis. (H) Attachments as viewed in the sagittal plane of the posterior back muscles and the orientation of their lines of pull on the second lumbar vertebra. Adapted from Adams et al (2002).

Interspinales: The interspinales muscles connect apposing spinous process edges and comprise thin rectangular-shaped sets of fibres that are believed to contribute to proprioception rather than intervertebral motion (Adams et al. 2002).

The other posterior muscles are arranged in three columns and two layers and represent the muscles primarily responsible for controlling movement of the lumbar region (Adams et al. 2002). Multifidus, longissimus thoracis and iliocostalis lumborum are arranged from medial to lateral and arise from spinous processes, accessory processes and transverse processes, respectively (Adams et al. 2002). The latter two muscles each comprise two parts: deeper fibres that arise from the lumbar vertebra, and superficial fibres that originate from thoracic vertebrae and ribs, to then cover their respective lumbar segments. The thoracic parts of these muscles contribute to the erector spinae aponeurosis, the deepest layer of the superficial back muscles that overlies multifidus.

Multifidus: The lumbar multifidus (MF) comprises multiple fascicles that originate from the caudal tip and inferolateral aspect of the spinous process and adjacent lamina at one vertebral level. Fascicles project inferolaterally toward their caudal attachments to the facet joint (Lewin et al. 1962; Jemmett et al. 2004), mamillary process, lamina, medial posterior superior iliac spine (PSIS), and dorsal sacrum, either two, three, four or five levels below (Macintosh et al. 1986; Jemmett et al. 2004). Fibres that project distal to L5 attach to aspects of the posterior ilium and/or sacrum. Superficial and deep components of MF can be differentiated from anatomical (Macintosh et al. 1986; Jemmett et al. 2004), biomechanical (Bogduk et al. 1992) and neuromuscular (Moseley et al. 2002; Dickx et al. 2010) perspectives, with an indication that deep fascicles comprise predominantly slow-twitch fibres that function tonically (MacDonald et al. 2006; Dickx et al. 2010). Although variation exists between individuals, deep MF fascicle length extends two vertebral levels, while superficial MF cross more than two (Macintosh et al. 1986; Adams et al. 2002; Jemmett et al. 2004). Deep MF is credited with controlling shear and torsion through intervertebral compression, rather than associated rotational torque (Macintosh et al. 1986; McGill 1991; Bogduk et al. 1992; Jemmett et al. 2004). While superficial MF produces extension and compression of the lumbar spine, in combination with the erector spinae (Macintosh et al. 1986; Bogduk et al. 1992). However, active segmental stabilisation of the vertebral motion segment is believed to require multi-muscle coordination (Macintosh et al. 1986; Bogduk et al. 1992; Cholewicki and VanVliet 2002; Jemmett et al. 2004).

Longissimus thoracis: Longissimus thoracis pars lumborum (LTL) lies immediately lateral to MF, arising from the accessory processes of L1 to L4 and converging to a common tendon that inserts superior to the posterior superior iliac spine on the ilium (Adams et al. 2002). LTL fibres originate from the transverse process to insert anterior to the common LTL tendon. Bilaterally this muscle acts to extend the lumbar vertebrae or control their flexion, while unilaterally the fibres contribute to lateral bending (Adams et al. 2002).

Longissimus thoracis pars thoracis (LTT) constitute a series of muscle bellies that arise from thoracic transverse processes (T1-T12) and posterior ribs (T4-T12) passing the lumbar region where their caudal attachment forms the medial aspect of the erector spinae aponeurosis to cover MF and LTL (Adams et al. 2002). Individual tendons systematically insert to the lumbosacral spinous processes, which make up a longitudinal bundle that constitutes the deep supraspinous ligament. LTT fibres indirectly facilitate lumbar extension by exerting an extension moment along the region (Adams et al. 2002).

Iliocostalis lumborum: Iliocostalis lumborum pars lumborum arises from the L1-L4 transverse process tips and inserts into the iliac crest. Like the LTL it acts bilaterally to extend the lumbar vertebrae or control trunk flexion, while unilaterally the fibres contribute to lateral bending (Adams et al. 2002). Iliocostalis lumborum pars thoracis muscle bellies arise from the lowest eight rib angles and attach to the iliac crest via long caudal tendons that comprise the lateral erector spinae aponeurosis (Adams et al. 2002). Like the LTT its fibres indirectly exert an extension moment on the lumbar vertebrae.

2.2.8 Nerve supply of the lumbar region:

Normal discs are considered largely avascular and aneural except for the outer AF and bordering longitudinal ligaments where free nerve endings have been noted (Bogduk et al. 1981; Bogduk 1983). Groen et al. (1990) indicate an abundant neural plexus derived from the sinuvertebral nerve via the rami communicantes in the ALL and PLL, with a combination of somatosensory and sympathetic afferent supply. Broadly, there is a predominantly sympathetic and multi-segmental distribution for anterior and middle column structures in contrast to that identified posteriorly to be more localised and unilateral (Groen et al. 1990). Roberts et al. (1995) demonstrated mechanoreceptors in the outer disc anulus and longitudinal ligaments, indicating a potential proprioceptive function for these formations, which confirmed the earlier suggestion of Malinsky (Malinsky 1959). Dorsal rami between L1-4 form medial, lateral, and intermediate branches, while that at L5 is longer and only branches medially and laterally (Bogduk et al. 1982). Each lumbar medial branch innervates its two adjacent facet joints and fibres of multifidus that arise from the spinous process of the same level (Bogduk et al. 1982). Lateral and medial branches distribute to iliocostalis and longissimus, respectively (Bogduk et al. 1982).

2.2.9 Summary:

Spinal classification, the lumbar vertebral body, disc, zygapophysial joints, ligaments, muscles and nerve supply have been reviewed.

2.3 Degenerative anatomy of the lumbar spine

2.3.1 Introduction:

Kirkaldy-Willis and Farfan (1982) proposed a three-stage hypothesis to functionally describe spinal degenerative changes: temporary dysfunction, an unstable stage, and a stabilisation phase. Spinal degenerative changes that characterise the unstable stage include: disc degeneration, facet joint osteoarthritis, ligament degeneration, and muscle alterations (Leone et al. 2007). The process involved is often referred to as a degenerative cascade, where the duration of each part varies markedly, with no definitive signs or symptoms distinguishing them (Farfan 1973; Kirkaldy-Willis and Farfan 1982). The first phase of the model is associated with mild and reversible anatomic changes. The second is characterised by reduced disc height, ligamentous laxity, and posterior element degeneration. While the third phase is distinguished by osteophytic projections and marked disc space narrowing that ultimately results in reduced motion (Kirkaldy-Willis and Farfan 1982). The two lowest lumbar motion segments are those most often affected, degenerating earlier and progressively with increasing age (Lewin 1964; Taylor 1975; Twomey and Taylor 1987; Butler et al. 1990). Although contention exists, it is generally held that discs degenerate before facets as the primary event in progressive degeneration (Vernon-Roberts and Pirie 1977; Gotfried et al. 1986; Butler et al. 1990; Fujiwara et al. 1999; Vernon-Roberts et al. 2007). Decreased ranges of lumbar movement and increased 'stiffness' occurs with increasing age (Taylor and Twomey 1980). This may be related to: osteoporotic (Dent and Watson 1966) and bony proliferative changes (Torgerson and Dotter 1976); increased collagen and reduced elasticity in intervertebral discs and spinal ligaments (Bogduk 2005); ankylosis of the zygapophysial joints (Adams and Hutton 1980); and diminishing muscle power (Macintosh and Bogduk 1987), either working in isolation or combination. The pathologies most relevant to the main investigation align with the unstable stage described by Kirkaldy-Willis & Farfan (1982) and will be outlined below.

2.3.2 Disc Degeneration:

A strong association between back pain and IVD degeneration exists (Luoma et al. 2000), yet despite this, the two are not synonymous (Battie et al. 2004). Disc degeneration and related clinical findings like the presence of osteophytes, disc narrowing and even herniation, can be asymptomatic (Paajanen et al. 1989; Boden et al. 1990), while the potential for severe sciatica and a painful herniated or prolapsed disc is well established . As such, there is no standard definition of disc degeneration (Urban and Roberts 2003; Battie et al. 2004). Discs degenerate earlier than other musculoskeletal tissues (Boos et al. 2002), with degeneration increasing steeply with age (Twomey and Taylor 1987; Miller et al. 1988). Distinction between anulus and nucleus of a degenerated disc is less obvious, the NP is more fibrotic, and disc morphology is disorganised (Buckwalter 1995). Internal clefts, fissures and concentric tears form, with cell proliferation, clustering and cell death present and associated with mucous degeneration and granular change (Urban and Roberts 2003) (Figure 2.4 (A)). Differentiation between age-related or pathological changes is difficult (Urban and Roberts 2003) with heredity now understood to play a dominant role (74%) (Ala-Kokko 2002), acting in combination with environmental factors (Battie et al. 2004). Perhaps the most significant result of disc degeneration in terms of the degenerative cascade, is the loss of disc height that may lead to: osteophyte development and pathologic changes to the vertebral body, and narrowing of the central spinal canal secondary to flaval and posterior longitudinal ligament bulging in combination with protrusion of the posterior disc, which may also compromise the inferior recesses of the intervertebral foramina (Fujiwara et al. 2000). Increased lumbar segmental motion (degenerative spondylolisthesis) occurs with increased disc degeneration (Fujiwara et al. 2000) and there is increased sensitivity of the degenerated disc to small changes in posture and movement (Dolan & Adams 2001).

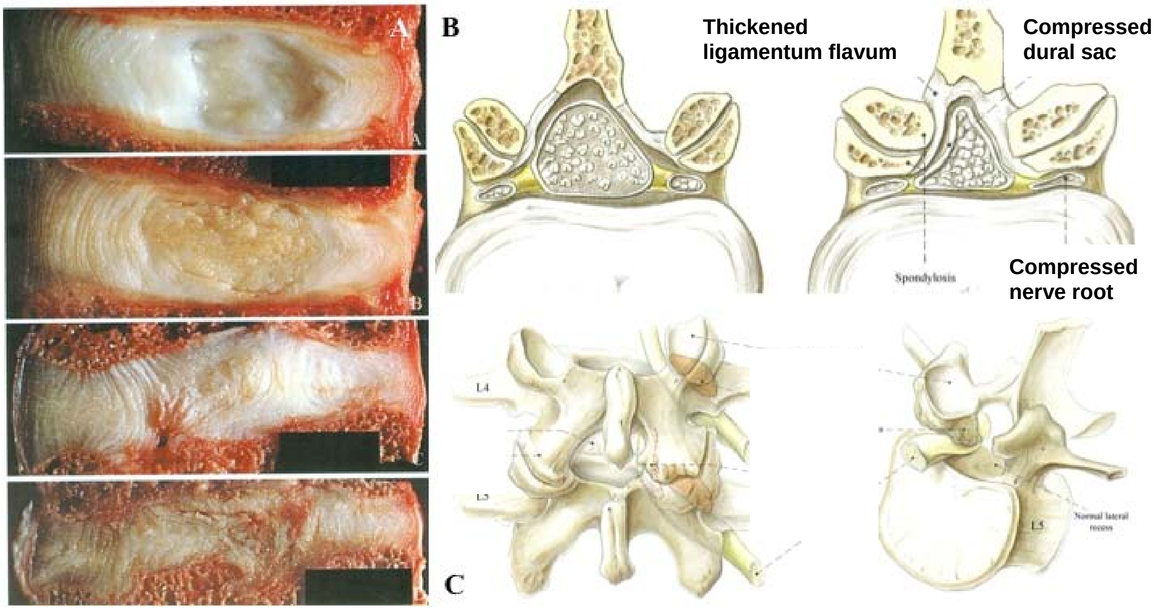


Figure 2.4: Illustrations indicating degenerative anatomy of the lumbar region. (A) Mid-sagittal sectioned lumbar intervertebral discs representing progressive stages of disc degeneration from a young healthy disc at the top to a severely degenerated one at the bottom. NP and AF distinction worsens alongside end-plate disruption and discolouration (Adams et al. 2002, Plate 1); (B) Normal spinal canal dimension (left) and central canal stenosis (right) and the consequently compressed dural sac and nerve root secondary to spondylosis and a thickened ligamentum flavum (Bauer et al. 1993, p342); (C) Spondylotic changes to the right L4/5 facet joint resulting in stenosis of the lateral recess and compression of the L5 nerve root (facet joint syndrome) (Bauer et al. 1993, p340).

The degenerative disc disease described here represents an indication for surgical treatment with the DIAM, wherein the purported distraction of the interspinous space aims to limit compression of the pain-sensitive posterior disc via tensioning approximating ligamentous structures (Taylor et al. 2007). This aspect is elaborated later in the chapter.

Herniated nuclear prolapse (HNP) involves displacement of nuclear and anular material beyond the normal disc perimeter, and typically into the vertebral canal and intervertebral foramen, whereby a compromised spinal nerve root may result in radicular pain (Bogduk 2005). HNP can be asymptomatic, it increases with advancing age, and excision of HNP material can relieve leg pain, but has a less effective impact on reducing back pain (Bogduk 2005).

2.3.3 Spinal Stenosis:

Lumbar spinal stenosis (LSS) is a condition wherein the AP and lateral diameters of the spinal canal and intervertebral foramina are narrowed, or have an abnormal shape secondary to developmental or degenerative processes, or a combination of both (Kirkaldy-Willis et al. 1974). Osseous or ligamentous hypertrophy, disc protrusion, and/or degenerative disc changes leading to degenerative spondylolisthesis (Kosaka et al. 2007), may result in a clinical presentation that involves neural tissue compression within the central spinal or lateral nerve canals, or neural foramina (Yong-Hing and Kirkaldy-Willis 1983; Arbit and Pannullo 2001) (Figure 2.4). The aetiology and pathogenesis of LSS has been extensively documented since its early reporting (Verbiest 1954,1955). LSS usually occurs beyond age 50 and is one of the most common degenerative conditions in the elderly. Three to four percent of patients in North America who attend a GP for low back pain have the condition, with a higher proportion (13-14%) reported for patients attending a specialist (Hart et al. 1995). The individual generally presents with low back and lower extremity pain, which is attributed to the degenerative cascade. Narrowing of the disc space results in overriding of the facets and/or infolding of the ligamentum flavum, or intra-canal protrusion of the posterior anulus, leading to a compromised canal space and therefore stenosis (Verbiest 1955; Evans 1964; Kirkaldy-Willis et al. 1978; Willen et al. 1997) [Figure 2.4 (B&C)]. A characteristic feature of LSS is neurogenic intermittent claudication (NIC), which is a posture-dependent condition (Verbiest 1954,1955) in which symptoms such as pain, altered sensation and weakness in the lower limb are exacerbated in positions of extension (standing and walking) and relieved in postures involving lumbar flexion (sitting or at rest) (Brish and Lerner 1964; Evans 1964; Kirkaldy-Willis et al. 1978). LSS associated radiculopathy is typically related to unilateral stenosis affecting the lateral recess or intervertebral foramen (Brish and Lerner 1964; Evans 1964; Kirkaldy-Willis et al. 1978). The mechanisms involving neural foraminal and canal space compromise during lumbar extension in LSS are well understood (Willen et al. 1997; Chung et al. 2000; Fujiwara et al. 2001). Surgical intervention can result in superior short term outcomes compared to conservative management (Costa et al. 2007; Malmivaara et al. 2007; Weinstein et al. 2008b), with open decompression the most prevalent operation employed to remove the source of neurologic compression (Ciol et al. 1996b; Katz et al. 1996). LSS is the primary condition toward which surgery with ISP devices have been directed, aiming to limit lumbar extension-induced canal and foraminal compromise (refer to next section). In their 1980's clinical trial, Johnsson et al (1992) reported that the majority of non-operated cases with LSS remained unchanged after four years with no evidence of severe deterioration (Johnsson et al. 1992). A later study reporting 10 year outcomes in LSS patients, reported no change in 70% of cases, with 15% each either improving or worsening as a consequence of the natural history of the disease (Amundsen et al. 2000).

2.3.4 Facet Joint Degeneration and Facet Joint Pain Syndrome:

Lumbar facet joints have been implicated in 15% to 40% of chronic low back pain (Schwarzer et al. 1995; Cavanaugh et al. 1996), although facet pain syndrome is reported as an unreliable clinical diagnosis (Jackson 1992). Pain of facet joint origin is typically manifest as local symptoms in the low back of a mechanical nature, deep and superficial muscle spasm, and associated posterolateral leg pain, which may be relieved by intra-articular injection with anaesthesia (Jackson 1992; Markwalder and Merat 1994; Cavanaugh et al. 1996; Dreyer and Dreyfuss 1996; Fujiwara et al. 1999; Tischer et al. 2006). Correlation between the severity of osteophytic degenerative changes apparent on radiographs, and clinical symptoms, is poor (Markwalder and Merat 1994; Cavanaugh et al. 1996; Fujiwara et al. 2000). Consequently, the effect of joint dysfunction on local soft tissues, including neovascular, intra-articular, capsule and myofascial structures, have been postulated as the potential source of pain (Bogduk 1983; Giles and Taylor 1987; Giles and Kaveri 1990; Cavanaugh et al. 1996; Fujiwara et al. 2000). Disruption of the facet joint capsule through posterior rotation of the inferior articular process has been shown secondary to forced and repetitive lumbar extension (Yang and King 1984). Hypertrophic facet degeneration may contribute to central and foraminal LSS (Yang and King 1984; Fujiwara et al. 2001).

2.3.5 Degenerative spondylolisthesis:

Intrinsic spinal stability is satisfactory under static conditions but challenged with motion where potential for an increased neutral zone exists in the presence of overstretched passive structures (Panjabi 1992). The biomechanical approach identifies instability with a loss of stiffness secondary to damaged or degenerated restraining structures that allows for segmental hypermobility beyond normal constraints (Frymoyer and Selby 1985; Pope et al. 1992a). This mechanism of segmental instability has been confirmed by studies describing sequential lesioning of tissues comprising the motion segment (Panjabi et al. 1977; Heuer et al. 2007). The presence of intervertebral instability is an important factor in determining surgical indication for spinal fusion and decompression (Leone et al. 2007).

Degenerative processes involving the IVDs and facet joints affect the stability of the motion segment (Farfan 1973; Kirkaldy-Willis and Farfan 1982; Frymoyer and Selby 1985; Fujiwara et al. 1999; Fujiwara et al. 2000). Various definitions of instability exist however a version applicable to the spine and segment-based surgical interventions is described, and relates to stage II in the degenerative cascade described earlier (Kirkaldy-Willis and Farfan 1982; Pope et al. 1992b). Degenerative spondylolisthesis (DS) is a disorder wherein the whole upper vertebra, inclusive of the vertebral body and posterior elements, translates (or slips) in the sagittal plane relative to the lower vertebra (Verbiest 1975). Unconstrained torsion is reported to be a major causative factor (Farfan 1973). DS differs from spondylolytic or congenital spondylolisthesis, which have a pars interarticularlis defect or dysplastic facets, respectively (Frymoyer 1994).

Radiographically on lateral imaging, the entire vertebra including the spinous process, is translationally misaligned (Butt and Saifuddin 2005). A 10° increase in sagittal rotation and ≥4mm for sagittal translation at a single segment, are used to infer instability based on functional x-rays (Dupuis et al. 1985; Boden and Wiesel 1990). Alternatively, Posner et al (1982) define anterior translation in excess of 8% (L1/2 to L4/5) or 6% (L5/S1) of the vertebral body width, posterior translation greater than 9% (L1 to S1), and sagittal rotation in flexion greater than 9° (L1 to L5) or >1° (at L5/S1 alone) to indicate instability. These values compare similarly to those proposed earlier by Nachemson and colleagues for segmental instability (Nachemson et al. 1979). In DS, a mean slip around 14% is described in a cohort of 200 patients (Rosenburg 1975).

The clinical presentation of DS is varied, however low back and leg pain symptoms generally develop in patients older than 50 years (Frymoyer 1994). The etiology of DS is multifactorial with associations to disc degeneration, facet joint osteoarthritis and spinal stenosis (Sengupta and Herkowitz 2005). Back pain typically predominate leg pain, which can shift with a unilateral or bilateral emphasis, and neurogenic intermittent claudication (NIC) secondary to dynamic neuroischaemia is commonly present and the primary reason for referral for surgery (Frymoyer 1994).

2.3.6 Summary:

Degenerative processes affecting the lumbar region including disc degeneration, spinal stenosis, facet joint pain syndrome, and degenerative spondylolisthesis are reviewed as the pathological conditions regarded as clinical indications for surgery employing interspinous implant.

Part 2: THE SURGICAL TREATMENT OF LUMBAR SPINE DISEASE WITH INTERSPINOUS IMPLANT

In this section the surgical treatment of lumbar degenerative disorders is reviewed, with particular attention paid to the interspinous implant (ISP) as an augmentation of other decompressive lumbar surgeries. The role of surgery in the treatment of low back pain is initially briefly discussed. The primary decompressive surgeries that may be augmented with ISP implants are outlined next and a published review paper that discusses literature relating to the four most investigated devices available, while revealing emerging ISPs that represent contemporary developments in the field are presented to complete this part of the literature review.

2.4 Surgical treatment for the degenerative lumbar spine

Wide geographic variations in the practise of lumbar spine surgery exist between and within countries, despite a similar biology and population back pain rate (Deyo and Mirza 2009). Australian surgeons operate for back pain at less than half the rate of those in the USA, and at double the rate performed in the UK (Cherkin et al. 1994). An optimal rate of surgery remains undetermined and appears dependent on various influences that are difficult to measure in isolation. These known international differences attract questions regarding the potential for excessive or suboptimal use of surgery in the treatment of back pain (Cherkin et al. 1994; Deyo and Mirza 2009). Consequently, quality assurance commentators are assessing the value of surgery, and attempting to weigh patient risk and economic cost, against potential benefit (Gibson and Waddell 2007a; Deyo and Mirza 2009).

Comparative studies between surgery and non-surgical treatment, placebo or the natural history continue to be a major focus for enquiry in the treatment of low back pain disorders (Gibson et al. 1999; Weinstein et al. 2006; Gibson and Waddell 2007a; Deyo and Mirza 2009). In individuals with sciatica, similar long-term outcomes have been found for surgical and non-surgical care, with a short-term advantage for surgery (Gibson and Waddell 2007a; Peul et al. 2008; Deyo and Mirza 2009). The importance of any early benefit of surgery on patient outcomes and quality of life continues to be widely debated. Operative interventions are being scrutinised in order to better understand their potential application.

A patient may become a surgery candidate when they have exhausted nonoperative management without pain relief (Gardner and Pande 2002), typically having had persistent symptoms beyond a 12 week period (Deyo et al. 2004). Surgical intervention for lumbar spinal disorders may be indicated in the small proportion of cases deemed psychologically healthy, and in whom the source of their pain and/or mechanical compromise has been verified through clinical assessment and imaging such as computed tomography (CT), magnetic resonance imaging (MRI), and discography (where appropriate) (Gardner and Pande 2002). Open spinal fusion is essentially considered an end-point option when an individual has been unresponsive to conservative, pain and minimally-invasive surgical management of their spine-related symptomology (Chiu 2004).

Figure 2.5 depicts a potential treatment algorithm for a patient experiencing low back pain. The figure does not represent an absolute clinical pathway but expresses instead a typical pattern of progression; variations in the individual patient and the opinions of health professionals are acknowledged. Surgery with ISP implant is considered a mini invasive surgery that may be indicated after failure of conservative and pain management treatments and to precede or augment more invasive procedures like rigid spinal fusion (Bono and Vaccaro 2007).

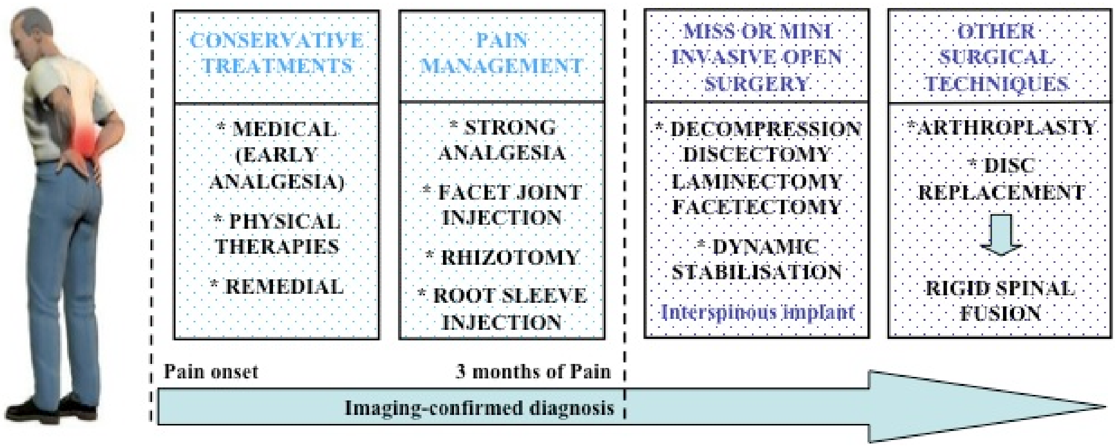


Figure 2.5: Diagrammatic representation depicting a common treatment algorithm for the surgical management of low back pain. From the onset of symptoms, patients have generally experienced pain for longer than 3 months, have undergone failed conservative and pain management treatment alternatives within that period, and have an imaging-confirmed diagnosis. These steps are prerequisites for consideration for mini invasive open surgery as the first surgical option, which includes interspinous device implantation. Rigid spinal fusion is considered end-point surgery for low back pain.

New systems for surgical treatment for low back pain continue to be developed (Weinstein et al. 2003; Deyo et al. 2004; Gray et al. 2006). Decompression and ISP-based surgeries involve a mini invasive, open, muscle-sparing approach via a small incision (Fraser and Hall 1993). Minimally invasive spine surgery (MISS) has subsequently evolved by employing the smallest possible incision usually by using a tube, endoscope or percutaneous approach (Jaikumar et al. 2002). Some of the earliest MISS examples were reported as early as the beginning of the last century, with muscle sparing techniques at the forefront of developments in surgical decompression (Fraser and Hall 1993). Advances in image guidance systems, endoscopy, lasers and disease observation tools have provided increased opportunity for less destructive methods (Jaikumar et al. 2002). MISS techniques are promoted to represent advances in surgical treatment by limiting iatrogenic tissue injury, where smaller wounds are purported to: reduce patients' post-operative recovery time and hospital stay, lessen their exposure to complications alongside a limited blood loss and fewer postoperative narcotics, and have an improved cosmetic outcome (Khoo et al. 2002; Isaacs et al. 2005; Park and Ha 2007; Fan et al. 2010). Evidence indicates that muscle-sparing surgeries to the lumbar region result in less change to MF and less postoperative back pain and functional disability than more conventional open approaches (Kim et al. 2006a; Fan et al. 2010). The potential for wider application of these less destructive surgeries are being explored for the aging populous, particularly for those patients with comorbidities that were previously considered contraindicating to surgical intervention (Gibson and Waddell 2007b). ISP implants represent a relatively new surgical option that have undergone several developments since the mid 1990's (Minns and Walsh 1997; Christie et al. 2005; Bono and Vaccaro 2007; Khoueir et al. 2007; Crawford et al. 2009c). The surgical approach for implanting an ISP is perhaps less invasive than a traditional open one however, typically involves unilateral myofascial morbidity due to its midline incision and subperiosteal technique.

2.5 Decompressive surgery in the lumbar region

2.5.1 Introduction

Spinal decompression, or fusion surgery with/without decompression, are commonly available surgical options considered for treating symptomatic lumbar spinal stenosis, degenerative spondylolisthesis, herniated or degenerative disc disease or facet joint osteoarthritis (primarily with radicular pain) (Grob et al. 1995). Lumbar discectomy and decompression for spinal stenosis, arguably represent the most common and long-standing spine surgeries (Armin et al. 2008). Although the pathophysiology of disease mechanism differs, each involves neural tissue compression within the central or lateral spinal recesses. Hypertrophied ligamentum flavum, osteophytic facet joint(s) or a herniated intervertebral disc, represent the most probable contributors (Schonstrom et al. 1989; Danielson and Willen 2001; Willen and Danielson 2001). Compared to the posterior disc anulus, the ligamentum flavum has been reported as the dominant structure involved in narrowing the central spinal canal during axial loading (Hansson et al. 2009).

2.5.2 Decompression techniques:

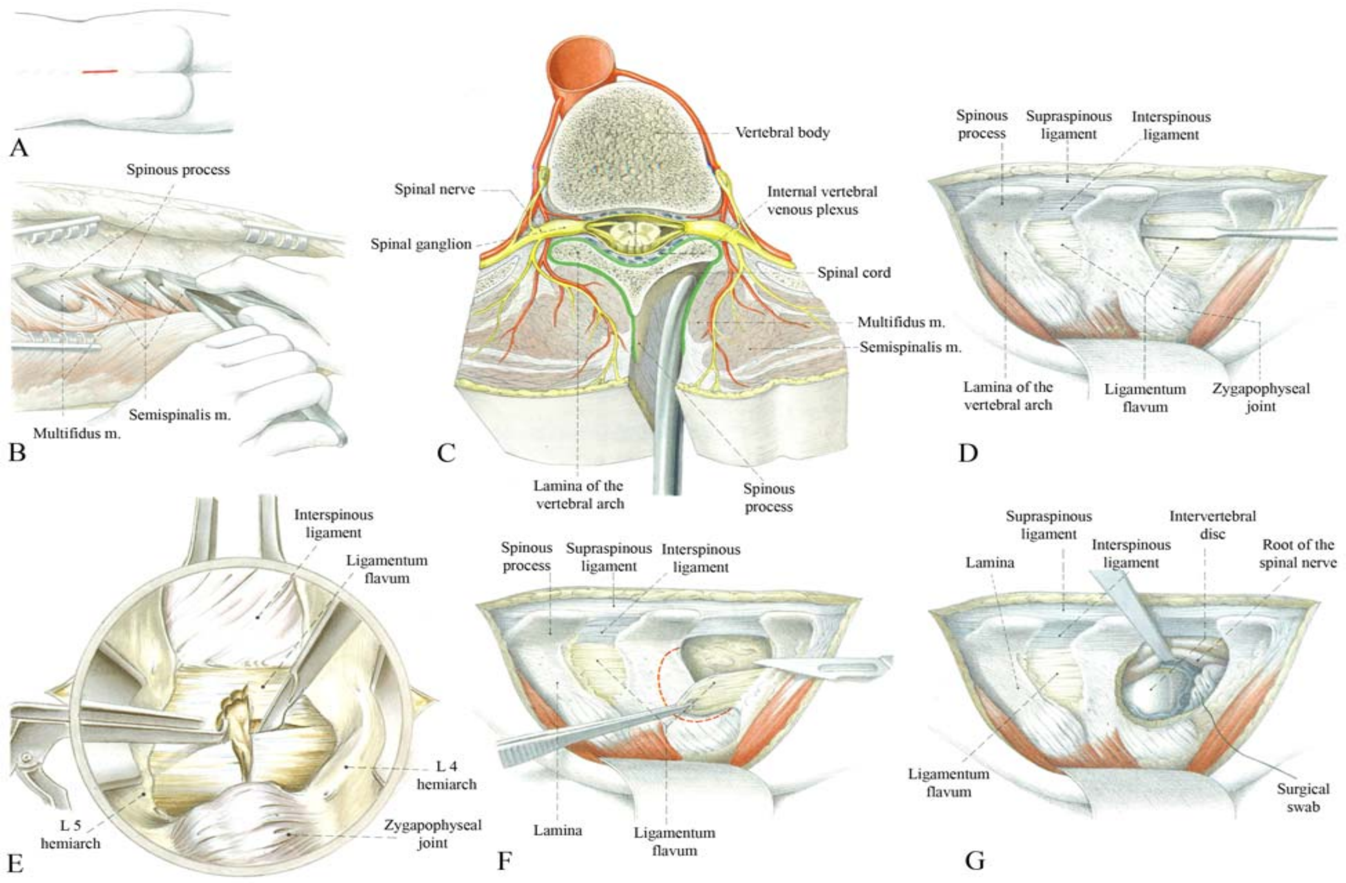
Decompression surgery aims to alleviate pain caused by nerve compression and involves removal of a portion of either bone (laminectomy, laminotomy and/or facetectomy, foraminotomy), or disc material (discectomy), in the region of the compromised nerve, thereby providing additional space for any affected neural or pain-sensitive tissues. Generally, a common surgical approach (Fraser and Hall 1993) is used involving: a 3-5cm median sagittal incision, made with the patient in slight flexion in prone; local myofascial attachments, including the multifidus and erector spinae muscles, are dissected from the spinous process and reflected off the lamina via a subperiosteal approach; this reveals the unilateral posterior vertebral arch; the ligamentum flavum is resected to expose the central canal and extradural structures. Aspects of this surgical technique are illustrated in Figure 2.6. Decompressive surgeries relevant to the main study are outlined below.

Laminectomy: Conventional (total) laminectomy involves surgical removal of the entire posterior arch of an index vertebra between bilateral laminae, including any overlying connective tissue and ligaments. An unwanted by-product of total laminectomy is the potential for increased segmental instability as a consequence of removing the associated local ligaments (Johnsson et al. 1986; Lu et al. 1999). The absence of one or more spinous processes after laminectomy precludes the use of an ISP device where bony anchorage is required.

The evolution of laminectomy to maximise decompression while maintaining spinal integrity has led to less invasive surgery where tissue preservation is the key aim (Weiner et al. 1999). Divergent from total laminectomy, in hemilaminectomy or laminotomy, the spinous process and associated structures are spared, and a single unilateral lamina is totally or partially removed, respectively (Bauer et al. 1993). Laminotomy removes a portion of unilateral lamina from one or adjacent vertebrae according to the neural elements requiring excision. Variations of laminotomy according to primary disc excision are represented in Figure 2.7. Bilateral laminotomy affords superior stability compared to traditional total laminectomy due to the retention of the spinous process and related ligaments (Tai et al. 2008). These lamina-based procedures all require midline microdecompression and therefore involve detachment of paraspinal muscles. A relatively new decompression technique involves longitudinal splitting of the spinous process into two halves, which is purported to leave its muscular and ligamentous attachments undisturbed (Watanabe et al. 2005; Shetty et al. 2010). This is followed by standard decompression of the offending tissues with minimal muscle dissection off the lamina (Watanabe et al. 2005; Shetty et al. 2010).

Discectomy: Mixter and Barr established a relationship between disc herniation and neural compression, and credited with being the first to report surgical excision of disc material involving a hemilaminectomy via an open technique (Mixter and Barr 1934). Use of an operating microscope was introduced in 1977 enabling less destructive surgery (Porchet et al. 2009). Microdiscectomy generally involves a small mid-sagittal incision, reflected muscle and nerve root tissue to afford access to remove offending nuclear disc material. Microdiscectomy is combined with laminotomy to achieve access for adequate decompression (Figure 2.7).

Figure 2.6: Schematic illustration of the progressive surgical technique used in a decompressive laminotomy. A small midline incision (A) is made, the paraspinal musculature are resected and reflected (B) to enable a subperiosteal (green layer) approach (C) to the lamina, intervertebral and interspinous structures (D) where the ligamentum flavum is excised using a punching rongeur (E) enabling visibility of the spinal canal and region of lamina requiring removal (circled red in F) which is then excised for decompression and exposure of any offending neural tissues. All images adapted and compiled from Bauer et al (1993).



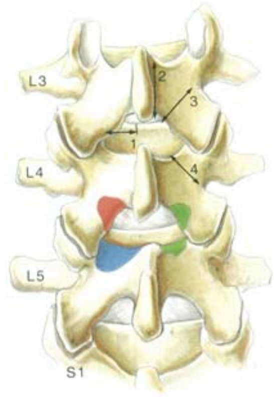


Figure 2.7: Various laminotomy options used to excise the offending herniated disc tissue requiring decompression. Green: Laminotomy in mediolateral disc herniation at the level of the intervertebral space. Red: Laminotomy in cranial positioned herniation with the facet joint largely preserved. Blue: Laminotomy in caudally positioned herniation where the facet joint is not opened (Bauer et al. 1993).

Facetectomy & Foraminotomy: An adjacent facet joint can be trimmed (facetectomy) or foramen opened (foraminotomy) to create further room for the exiting nerve.

2.5.3 Fusion surgery:

Fusion surgery aims to use a bone graft and adjunctive materials to fuse adjacent vertebrae. Bone grafts are either: autologous, as harvested from the patient; or an allograft, as derived from an external bone source. Bone morphogenetic protein products may be used to augment instrumented fusion. The methods for performing lumbar fusion vary to include: anterior (ALIF); or posterior lumbar intervertebral body fusion (PLIF); and posterolateral fusion (PLF) (Deyo et al. 2004). Three types of spinal instrumentation are used to provide increased stability: pedicle screws and rods; anterior; and posterior interbody cages (McAfee 1999). Lumbar fusion and decompression may be employed as adjunctive surgeries in cases where segmental instability already exists or is anticipated post-operatively (Carragee 2006). History of previous lumbar surgery, particularly spinal fusion, increases an individual's likelihood for further surgery due to adjacent level degeneration, or the development of segmental instability (Nachemson 1999; Deyo et al. 2004). Repeat surgery required in the short post-operative term, is generally considered undesirable, reflecting initial operation failure (Deyo and Mirza 2009). Outcomes after subsequent surgeries are commonly worse than those following the first, suggesting repeat surgery results are less successful (Deyo and Mirza 2009).

Maintained integrity of the posterior ligamentous complex, in particular that of the anchoring points for the supraspinous ligament and erector spinae aponeurosis, reduces the likelihood of developing segmental instability.

Contemporary non-fusion technologies are designed to enhance the segmental stability of the affected spine so as to minimise further strain and injury, while avoiding the complications and slower recovery of rigid motion-limiting fusions (Bono and Vaccaro 2007). The use of posterior dynamic stabilisation (PDS) for the treatment of spinal stenosis, nerve root compression, degeneration and instability is a claimed surgical advance that provides a non-fusion option

(Khoueir et al. 2007). These devices, of which pedicle-screw and interspinous implants are the primary examples, are promoted to improve clinical outcomes due to their minimally invasive, motion-restoring surgery. Investigations are beginning to quantify both the cost-effectiveness (Hannibal et al. 2006) and clinical utility for some of the PDS devices currently in use (Mayer and Korge 2002).

2.5.4 Summary:

Decompressive lumbar surgical techniques including laminectomy, laminotomy, discectomy, facetectomy and foraminotomy have been outlined. Lumbar fusion has been described as end-point surgery for which ISP implants are claimed to represent a less invasive surgical alternative.

The following section presents a review of interspinous implants in the surgical treatment of lumbar spine disease. This review is based on a published paper, and has been adapted to reflect new additions to the literature from the date of the paper's original submission (June 2009) and the date of writing (June 2010).

2.6 Interspinous implants

Surgical treatment of lumbar segment disease with interspinous implant: review

2.6.1 Introduction

Interspinous implants and dynamic pedicle screw systems represent non-fusion surgery alternatives in the treatment of lumbar segment disease (Khoueir et al. 2007). Development of ISPs in the 1990s reflected the move toward minimally-invasive spinal surgery, where retention of intrinsic stabilising structures was believed to offer advantages over conventional surgical methods (Khoueir et al. 2007). Collectively, these posterior dynamic stabilisation systems are employed to prevent adjacent segment overload by restoring physiologic load transmission (Minns and Walsh 1997; Sengupta 2004). This review will focus on interspinous implants.

An increasing number of ISP devices are available and appear to have a wide international use. First generation systems have now been modified (Minns and Walsh 1997; Sengupta 2004; Christie et al. 2005; Kong et al. 2007), while new options continue to be developed, tested and introduced clinically. The principle common to all ISP systems is an induced distraction of the interspinous space. Tensioning posterior structures like the ligamentum flavum and posterior anular fibres are believed to enlarge the central spinal canal and neural foramina, resulting in reduced approximation of pain-sensitive tissue with consequent relief of symptoms (Christie et al. 2005; Bono and Vaccaro 2007; Khoueir et al. 2007). ISP devices putatively limit symptom-producing motion, particularly in the sagittal plane, while allowing an otherwise full spinal range (Christie et al. 2005; Bono and Vaccaro 2007; Khoueir et al. 2007).

The purpose of this review will be to outline the design characteristics, material properties, clinical rationale and applications for four interspinous implants employed in the treatment of degenerative conditions of the lumbar spine. The Device for Intervertebral Assisted Motion (DIAM™; Medtronic Sofamor Danek, Memphis, USA), the Wallis™ implant (Abbot Laboratories, Bordeaux, France), the X-Stop™ (St Francis Medical Technologies, Almeda, USA), and the Coflex™ implant (Paradigm Spine, Wurmlingen, Germany) have been selected to represent the second-generation clinically most commonly employed interspinous implants. They are the subjects of the majority of published literature. Clinical trials currently investigating an ISP device will be outlined, to highlight directions in examining the utility of this surgical intervention.

2.6.2 Design and Surgical Technique Characteristics:

Interspinous implants vary in design, employing compressible (DIAM and Wallis) or rigid (X-stop and Coflex) composite materials including: bone allograft; titanium; polyetheretherketone;

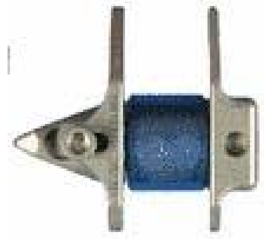
and/or elastomeric compounds (Khoueir et al. 2007). The DIAM is an X-shaped polyethylene-covered silicone wedge, with two removable polyethylene fixing cords that can be secured around adjacent spinous processes and fixed with a titanium crimp (Taylor et al. 2007). The Wallis implant was initially titanium; however the second-generation device utilises the increased elasticity of polyetheretherketone (PEEK) as the central spacer, secured with two polyethylene (Dacron) tapes to the spinous processes (Senegas 2002b). The X-Stop comprises an oval titanium spacer with bilateral titanium wings that are attached to adjacent spinous processes (Zucherman et al. 2004). The Coflex is a ‘U’ shaped titanium spacer with four wings that are crimped to the spinous processes to secure the implant (Wilke et al. 2008). Table 2.1 summarises the characteristics of these 4 devices.

In general, ISP devices act as a spacer between the spinous processes at one, or more symptomatic vertebral segments. They are manufactured in various sizes with their central diameter ranging between 6 to 15mm, providing an individualised application. The surgical technique is considered minimally invasive, employing a small incision of between 30 to 50mm along the median sagittal plane and adjacent to the spinous processes. The surgery is typically performed with the patient in prone, although the lateral decubitis position is used for X-Stop placement (Hsu et al. 2006). A relatively short period of general anaesthesia is required for the DIAM, Wallis and Coflex surgeries, with the X-Stop being the only interspinous implant reported to be inserted under local anaesthesia (Hsu et al. 2006).

A difference in the surgical technique between these four implants relates to the introduction of the implant into the interspinous space. Implanting the Wallis and Coflex requires resection of the interspinous and supraspinous ligaments, whereas the DIAM and X-Stop devices can be introduced through a punctured interspinous ligament, keeping the supraspinous ligament intact (Figure 2.8). The supraspinous ligament can be reattached with sutures when the Wallis and Coflex implants are in situ. Retention of the supraspinous ligament is believed to optimise stability at the implanted segment; a finding based upon fundamental investigations describing the tensile properties of lumbar spinal ligaments after serial lesioning (Hindle et al. 1990; Dickey et al. 1996). Figure 2.9 provides a schematic representation of the DIAM, Wallis, X-Stop and Coflex implants, as they would appear in the sagittal plane.

In the last decade, several new devices (in addition to the four already listed) have been introduced to the interspinous implant market, with a general progression toward the use of PEEK-OPTIMA® (Invibio Ltd, Thornton Cleveleys, UK) as their composite material. Table 2.2 summarises the primary material, and manufacturing or marketing affiliations for ten recently available devices (illustrated in Figure 2.10).

Table 2.1: Details for four interspinous implants currently used in the treatment of lumbar degenerative disorders. Material properties, sizes and primary indication details are outlined.

				
Device	Device for Intervertebral Assisted Motion (DIAM) Medtronic Sofamor Danek, Memphis, USA	Wallis Implant Abbot Laboratories, Bordeaux, France	X STOP Interspinous Process Decompression System St Francis Medical Technologies, Almeda, USA	Coflex Implant Paradigm Spine, Wurmlingen, Germany
Material	Compressible Polyethylene-covered silicone, polyethylene ligatures, titanium crimp	Compressible Polyetheretherketone (PEEK)[I], Polyester (Dacron) bands, titanium crimp	Non-compressible Titanium	Non-compressible Titanium
Sizes (mm)	8, 10, 12, 14	6, 8, 10, 12, 15	6, 8, 10, 12, 14	8, 10, 12, 14, 16
Primary indications	Posterior element degeneration	Herniated disc; Stenosis	Stenosis with NIC; Age>50	Posterior element degeneration

NIC=Neurogenic Intermittent Claudication; [I] Invibio® product (www.invibio.com – accessed 31 May 2009)

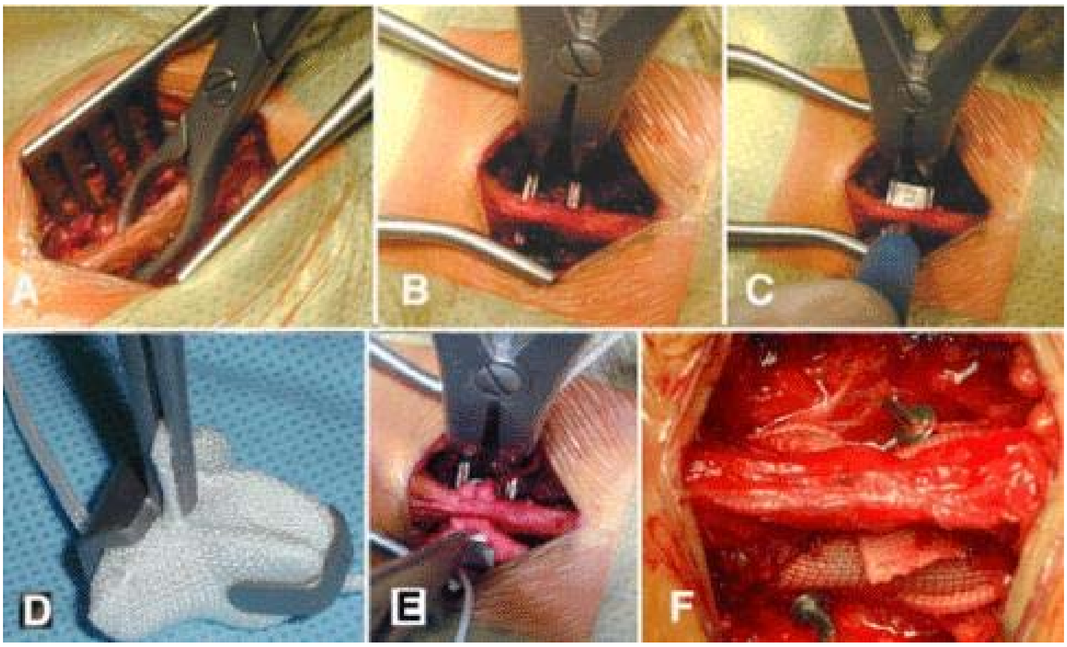


Figure 2.8: Diagram illustrating the DIAM surgical technique where the interspinous ligament is punctured (A), the interspinous space is sized for implantation (B & C), the DIAM is prepared for surgery using a specialised applicator (D), the DIAM is inserted into the interspinous space (E) where it sits underneath the retained supraspinous ligament (F). Image sourced from www.medtronic.com with permission.

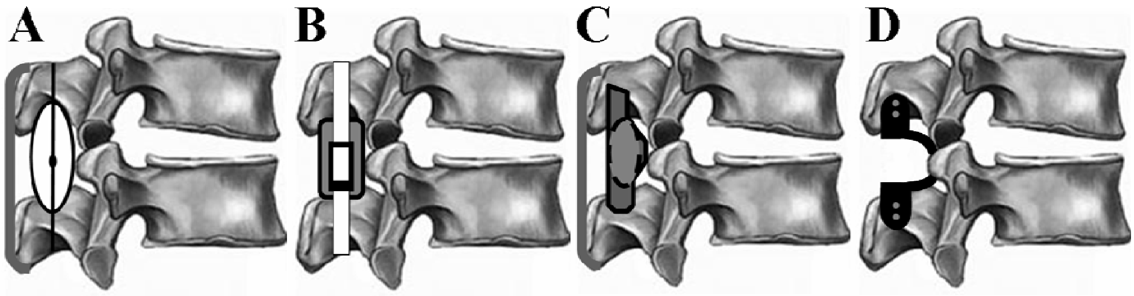


Figure 2.9: Schematic representation of the DIAM (A), Wallis (B), X-Stop (C) and Coflex (D) interspinous implants as they would appear in situ in the interspinous space of a lumbar motion segment. Retention of the supraspinous ligament in the surgical implantation of the DIAM and X-Stop devices is depicted.

Although the DIAM and X-Stop surgical techniques retain the supraspinous ligament, implanting these or the Wallis and Coflex devices requires bilateral exposure of the spinous processes with adjacent tissue retraction. Reported advantages for the new devices are a less invasive surgical approach that involves a unilateral or percutaneous insertion technique (Table 2.2) where purportedly less tissue is interrupted. Whether outcomes vary due to these subtle surgical differences remains undetermined. An optimal side from which to unilaterally approach the interspinous space for this procedure has not been reported and presumably reflects surgeon preference.

Table 2.2: Ten interspinous implant devices available for the surgical treatment of lumbar degenerative disease. Their primary material, surgical approach to implantation and company affiliation are outlined.

Device Name		Material	Approach	Company
[I]	Flexus™	PEEK-OPTIMA®	Unilateral	Globus Medical, USA
[II]	Impala®	PEEK-OPTIMA®	Unilateral	Signus Medizintechnik, Germany
[III]	InSpace®	PEEK; Titanium	Unilateral	Synthes Spine, USA
[IV]	InSwing®	PEEK-OPTIMA®	Unilateral	Blackstone Spine, USA
[V]	PercLID™	Titanium	Percutaneous	Kyphon & Medtronic, Belgium
[VI]	Promise	PEEK-OPTIMA®	Unilateral	Biomech-spine, Taiwan
[VII]	Rocker	PEEK-OPTIMA®	Unilateral	Biomech-spine, Taiwan
[VIII]	RODD	PEEK-OPTIMA®	Unilateral	Novaspine, France
[IX]	Superion™	Titanium	Percutaneous	Vertiflex Inc, USA
[X]	X-Stop[PK®]	PEEK-OPTIMA®	Unilateral	Medtronic, USA

[I]http://www.globusmedical.com/clinical_trials/clinical_trials.php
[II] http://www.signus-med.de/en/signus.html; [I]
[II]http://www.synthes.com/;
[IV]Gunzburg et al, 2009
[V]http://www.kyphon.com/uk/product.aspx?siteid=2 (Nardi et al. 2010);
[VI]http://biomech-spine.com/products/promise.html;
[VII]http://biomech-spine.com/products/rocker.html;
[VIII]http://www.novaspine.fr/;
[IX]http://www.vertiflex.net/;
[X]http://wwwp.medtronic.com/, development of the original X-Stop implant (Table 2.1) using PEEK as the primary material; PEEK-OPTIMA=polyetheretherketone; www.invibio.com; All accessed 31/5/2009.

2.6.3 Mechanism of Action:

Biomechanically, the DIAM, Wallis, X-Stop and Coflex implants have been shown to constrain motion in the sagittal plane, particularly extension, with minimal, if any constraint to either axial rotation or lateral flexion (Minns and Walsh 1997; Lindsey et al. 2003; Schiavone and Pasquale 2003; Phillips et al. 2006). The presence of an interspinous implant is commonly reported to affect the intervertebral relationship by distracting adjacent spinous processes; which in turn is believed to establish posterior tension through the introduction of mild segmental flexion (Christie et al. 2005) (Figure 2.11).

Biomechanical cadaveric investigations have shown that interspinous implants: tension the posterior disc anular fibres thereby dissipating posterior disc compressive forces (Swanson et al. 2003; Wilke et al. 2008); off-load the zygapophysial joints (Wiseman et al. 2005); and increase canal and foraminal area by tensioning the ligamentum flavum and posterior anulus of the intervertebral disc (Richards et al. 2005). These investigations are further elaborated in the discussion of this ISP review.

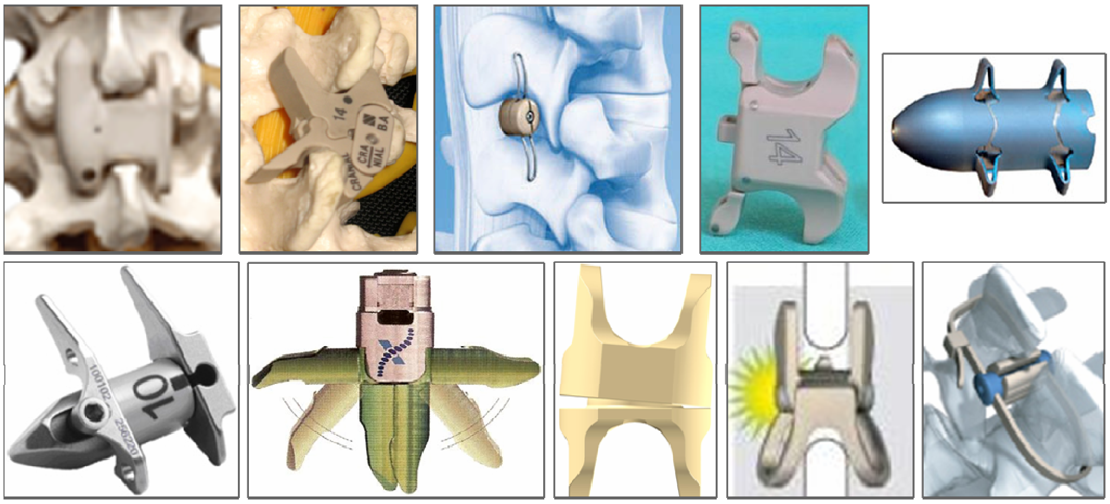


Figure 2.10: Montage depicting ten new interspinous implants as revealed in Table 2.2 (clockwise from top left): Flexus™; Impala®; InSpace®; InSwing®; PercLID™; Promise; Rocker; RODD; Superion™; X-Stop PK®. Images sought from the respective websites listed in Table 2.2 with permissions for use granted via separate emails in May 2009.

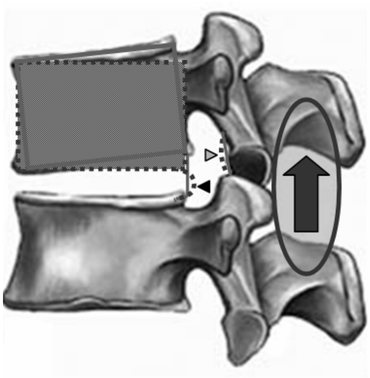


Figure 2.11: Schematic representation of the purported mechanical effect of an interspinous implant (ISP) (oval) as employed in a single lumbar motion segment. By distracting the posterior elements (large arrow), a subtle kyphosis (or flexion) of the cephalad vertebra in relation to the caudal one is thought to be imposed. This is believed to result in a tensioning of the posterior ligamentous structures [posterior anulus (dark arrow); ligamentum flavum (light arrow)] that leads to an increased foraminal space and reduced posterior intradiscal pressure.

In an analysis of sagittal motion using seven cadaveric L2-5 spines, Lindsey et al reported a 5˚ reduction in flexion-extension range in the presence of an X-Stop device implanted at L3-4 (Lindsey et al. 2003). The device significantly effected L3-4 during flexion-extension, shifting the segment's neutral point into 2˚ of flexion. In agreement with this finding, a reduction of 2˚ of segmental flexion-extension motion was observed by Siddiqui et al in 26 patients with lumbar spinal stenosis and neurogenic intermittent claudication who were assessed with upright MRI at 6 months after X-Stop surgery (Siddiqui et al. 2006b). The smaller effect noted in these patients as compared with the cadaveric spines of the Lindsey et al study (2˚ versus 5˚ reduced range, respectively) was attributed to the greater age of the clinical stenosis cases (range 57-93yrs), as compared with the cadaveric spines (age range 17-55yrs). The in vivo imaging study of Kim et al (2007) investigated the sagittal alignment of subjects receiving decompressive surgery alone, versus those receiving decompressive surgery augmented with a DIAM.

Results were obtained by comparing skeletal measurements from preoperative supine MRI, with those from prone intraoperative (implant in situ) x-ray films. No significant alteration to disc height was revealed for either group, however their inter-group comparison showed the decompression plus DIAM group to be 1.9˚ more kyphosed than those who received decompression alone. The noted difference related to an increased segmental lordosis in the decompression-alone group rather than detectable flexion in the DIAM cohort. The varied imaging sources compared in this study represented a limitation that made strong conclusions difficult. Sobottke et al (2009) reported a 3.8˚ initial intervertebral angle flattening at the index level in their 33 DIAM-implanted cases assessed in vivo using erect lateral radiography. This early change reverted toward preoperative angulation but remained relatively kyphosed at 6 weeks postoperatively (Sobottke et al. 2009). The study by Crawford et al (2009a) employed rasterstereography and radiography to assess lumbar lordosis in patients who received surgery augmented with a DIAM (detailed further in Chapter 6). These patients demonstrated a significant 3˚ reduction in regional lumbar lordosis at 6 weeks after surgery, and minimal flattening (NS) of the skeletal segmental angle at the DIAM-implanted level. In combination, these investigations provide limited support for the premise that a segmental kyphosis is induced in the presence of an ISP.

The study of Wilke et al (2008) assessed the effect of the DIAM, Wallis, X-Stop and Coflex devices on segmental motion and intradiscal pressure. Six human cadaveric spine segments (3x L2-3 and 3x L4-5) per implant (to total 24) were tested in three modes; intact, defect-induced, and with an ISP device implanted. Creation of a standardised defect, consisting of bilateral hemifacetectomy and resection of both flaval ligaments, led to a slight kyphotic tilt of each segment (range 0.5˚-0.7˚) and an increased range of motion in all directions. After device implantation, the segmental kyphosis was further emphasised with the DIAM, but remained unaffected by the other three implants. All implants were shown to have a stabilising effect in extension with a median of 50% less range than the intact state. The Wallis implant restabilised the segment into flexion, while the other three allowed more range than in the intact state. Compared to the defect, all four implants behaved similarly in having neither a significant stabilising nor destabilising effect on either lateral bending or axial rotation.

Phillips et al (2006) provided further support for the stabilising role of the DIAM device when applied to cadaveric L4-5 segments. Insertion of the DIAM after facetectomy-discectomy restored flexion-extension motion to below the intact state without eliminating segmental mobility. Additionally, the DIAM was effective in reducing the increased segmental range resultant from discectomy, in positions of flexion and extension. In lateral bending, the DIAM reduced motion after discectomy to approximate the intact state; however it did not alter the increased rotational range. The effect of DIAM on segmental motion in vivo has not been reported in the literature identified in searches for this review.

Wilke et al (2008) showed intradiscal pressure (IDP) to be strongly released in extension for all four implants, remaining unaltered in flexion, lateral bending and axial rotation. This finding agreed with an earlier cadaveric study by Swanson et al (2003) who revealed a reduced IDP at X-Stop-implanted levels in both neutral and extension. Swanson et al also showed no change to IDP at adjacent levels as a result of X-Stop placement, suggesting a segmentally isolated effect. However, the cadaveric study of Lindsey et al (2003) revealed a 0.8˚ reduction in motion between neutral and extension at the L4-5 segment adjacent to an L3-4 X-Stop implant. The effect on facet loading during extension of an X-Stop device implanted at L3-4 was investigated by Wiseman et al (2005) in seven loaded cadaveric spines using pressure-sensitive film placed in the facet joints at implanted and adjacent levels. Their results indicated that the implant reduced the mean peak pressure (by 55%), average pressure (by 39%), contact area (by 46%) and force (by 67%) of the facet joints at the implanted level, generally without effecting adjacent levels [except the contact area at L2-3 (increased by 24%)]. They concluded that interspinous decompression with X-Stop was unlikely to cause either adjacent facet pain or facet joint degeneration, and instead may relieve pain induced by pressure at the facets or posterior anulus, which was in agreement with a foundation study by Minns and Walsh (1997).

An in-vivo study by Siddiqui et al (2006a,b) used upright MRI to measure changes in canal and foraminal dimensions in varied postures: erect standing; neutral sitting; sitting in flexion; and sitting in extension. In the presence of an X-Stop device, spinal canal area (SCA) was increased in all postures but only significantly in seated neutral (by 21%), and erect standing (by 23%) for single-level implantation. Double-level surgeries showed increases to SCA in erect standing (cranial segment by 19%; caudal segment by 21%) and seated-extension (cranial segment by 18%; caudal segment by 15%). Foraminal area was increased for the left side in both seated extension (by 20%) and seated flexion (by 19%) in the single-level cases, and right cranial (by 27%) and caudal (by 20%) levels, and at the left cranial (by 32%) level on extension in double surgeries. The authors attributed the noted non-uniformity between left and right sides to anatomical variability in stenosis between cases rather than any measurement difference. Increased spinal canal and foraminal area (at least on one side) was noted, particularly in erect standing, at 6 months after surgery with the X-Stop device (Siddiqui et al. 2006a,b).

2.6.4 Clinical Indications:

The clinical goal motivating interspinous implant development was the requirement for dynamic stabilisation in patients primarily with spinal pathologies of the posterior elements (Minns and Walsh 1997). Spinal stenosis of the canal and foramen, and facet arthropathy, represented the initial conditions for which these devices were indicated (Minns and Walsh 1997). These spondylosis conditions are known to deteriorate with age, and increase in prevalence craniocaudally in the lumbar spine (Andersson 1999). It is generally held that lumbar spondylosis occurs after, and in response to degenerative disorders of the disc, with increased posterior joint loading resulting from a consequent loss of disc height (Andersson 1999). Surgeons therefore attempt to unload the facet joints and restore segmental height, while providing sufficient stability, particularly in symptomatic positions, typically extension (Christie et al. 2005; Taylor et al. 2007; Wilke et al. 2008).

Purportedly to delay the onset of spinal stenosis and facet joint arthropathy, interspinous implants have been recently employed in the treatment of degenerative disc disease and the associated segmental instability (Christie et al. 2005). This clinical indication represents a relatively new application for these devices; however little clinical evidence is currently available to substantiate their role. Published clinical evidence available for each device is summarised in Table 2.3 and outlined in the text to follow.

DIAM: Improvement in quality of life variables, particularly pain, function, and patient satisfaction, have been reported for the DIAM implant (Caserta et al. 2002; Schiavone and Pasquale 2003; Mariottini et al. 2005; Kim et al. 2007; Taylor et al. 2007; Crawford et al. 2009a). Evidence supporting the application of the DIAM to specific pathologies remains limited as a result of the range of clinical diagnoses included in these investigations. The publication by Taylor et al (2007), who developed the DIAM, identifies three broad indications for DIAM surgery: discogenic disease; posterior element disease (stenosis, facet degeneration and grade I spondylolisthesis); and augmentation of an existing lumbar fusion through prevention of consequential adjacent segment disease (Taylor et al. 2007). Variable reports exist for repeat lumbar surgery required after initial DIAM implantation (Table 2.3) (Taylor et al. 2007; Crawford et al. 2009a).

Wallis: The Wallis system has been suggested as indicated in disc disease including: large herniation; recurrent herniation; disc degeneration adjacent to rigid fusion; and Modic type I changes (Senegas 2002b). Clinical effectiveness is supported by investigations that showed improvement in patient-reported pain and function (Senegas 2002b; Floman et al. 2007). However, one study (Floman et al. 2007) reported recurrent herniations in 5 of their 37 cases occurring between 1 and 9 months after the initial surgery, all at the L4-5 level, and resulting in additional surgery in 2 cases. This rate of repeat lumbar surgery after Wallis implantation was similar to that described by Senegas et al (2002b) (3/40 cases). A long-term survivor analysis of patients receiving Wallis-augmented surgery indicated that 24% and 11% of their 142 cases, required further lumbar surgery or implant removal, respectively, before 9-15 years following the original Wallis implantation (Senegas et al. 2007). The Wallis is reported to reduce adjacent segment degeneration above lumbosacral instrumented fusion (Korovessis et al. 2009).

Table 2.3: Published studies reporting outcomes following lumbar surgery with the DIAM, Wallis, X-Stop and Coflex interspinous implants.

Author, Year	**Sample**	**Conditions (cases)**	**Surgery (cases)**	**HRQoL**	**Follow-up**	**Findings (cases)**
DIAM						
Crawford et al, 2009	39; 21F, 18M; 51yrs (23-85)	Anatomical: Disc (25); Facet (14). Nerve root compression (11); Facet Joint Pain (7); Segmental Instability (21)	Augmentation (39)	MODEMS: Pain; ODI; Satisfaction	B; 6w; 3, 6, 12, 24m	Improvement best at 6m: Pain by 23.4%; ODI by 13.5%; Failed 11/39
Kim et al, 2007	31; 15F, 16M; 51yrs (27-74)	Recurrent disc herniation; Large disc herniation with radiculopathy; Spinal stenosis	Augmentation (31): Compared with decompression alone	VAS (back and leg pain); modified Macnab	B; Day1; 1 week; 3m; 12m (mean)	Improvement due to decompressive surgery only
Taylor et al, 2007	104; 49F, 55M; 51yrs (25-86)	Herniated disc (60); Disc disease (42); OA foraminal stenosis (37); Soft stenosis (6); Bulging disc (2)	Isolated (9); Augmentation (95)	Dallas Pain Questionnaire; Incidence data	B; 6m; 18m	(92/104) relieved; Failed 11/104 (repeat DIAM 5/11)
Mariottini et al, 2005	43; 17F, 26M; 54yrs (34-80)	Soft stenosis (36); Canal stenosis (7); Mild instability (23/43)	Augmentation (43); Single level (31)	Dallas Pain Questionnaire; Henderson Classification	Various: 12m-5yrs (mean n/a)	Overall: Excellent (18); Good (22); Neutral (3)
Schiavone & Pasquale, 2003	42: 22 DIAM alone: 9F, 13M; (31-51yrs)	Disc segment degenerative disease	Isolated (22); Augmented pedicular synthesis (20)	Excellent, Good, Fair, Poor Rating scale	Various: mean 10m	Mean: Excellent (16); Good (4); Fair (2); Poor (0)
Caserta et al, 2002	82; n/a; 43yrs (n/a)	Degenerative disc disease (41); Disc herniation (21); Recurrent disc herniation (9); Instability (5); Spondylolisthesis (2); Stenosis (4)	Isolated stabilisation (57) & laminectomy (4/57); Combined (fusion) stabilisation (25)	Not declared	Various: mean 20m (1-6yrs) for 61/82 only	Satisfactory
Floman et al, 2007	37; 14F, 23M; 36yrs (15-58)	Primary disc excision (33); Recurrent herniation excision (4). Voluminous disc herniation with >50% height preservation	Augmentation (37); L4-5 (32), L3-4 (3), L2-3 (1), L1-2 (1)	Last 14: ODI; VAS (back & leg)	3, 6w, 6, 12m (mean 16m)	ODI: improved 30%; VAS back improved 52%; VAS leg improved 67%; re-herniation 5/37; Failed 2/37
Wallis Senegas et al, 2007	142; 37F, 105M; 47yrs (n/a)	Degenerative instability due to: Canal stenosis; Recurrent disc herniation; Large herniation	Augmentation (132)	Survivors analysis	9-15yrs	Lumbar surgery 34/142; Implant removal: 9/37F, 17/105M; Survival at 10yrs 83% (118/142)

Senegas et al, 2002	40; 11F, 29M; 42yrs (25-62)	Reherniated L4-5 disc (40)	Augmentation (40); compared to micro alone	VAS (back and leg pain); medication use; ODI	Various: mean 37m	VAS back improved 74%; VAS leg improved 92%; Failed 3/40
X-Stop						
Hsu et al, 2006	100; 43F, 57M; 70yrs	Single leg stenosis (64%)	Augmentation (100); compared to non-operative treatment group	SF-36	B; 6w; 6, 12, 24m	PCS 11pt improvement; MCS 3 pt improvement (2yrs); Failed 7/100
Kondrashov et al, 2006	18; N/A; 67yrs	Degenerative spondylolisthesis (6/18);	Single (12/18), dual (6/18)	ODI	Mean 51m (45-61)	Pre ODI: 45 (20-80); Post ODI 15 (0-36); 29% mean improvement; >15% 14/18
Zucherman et al, 2005	93/100; 43F, 57M; 70yrs	Single leg stenosis (64%)	Augmentation (100); compared to non-operative treatment group	ZCQ	B; 6w; 6, 12, 24m	Superior to non-operative. SS: 56/93; PF: 53/93=clinical improvement; Satisfied 68/93; Failed (laminectomy) 6/93;
Zucherman et al, 2004	100; 43F, 57M; 70yrs	Single leg stenosis (64%)	Augmentation (100); compared to non-operative treatment group	ZCQ	B; 6w; 6, 12m	Superior to non-operative. Overall success 59% (12m)
Coflex						
Kong et al, 2007	18; 15F, 3M; 62yrs (41-71)	L4-5 spinal stenosis with mild segmental instability (18)	Foraminal decompression & partial laminotomy (18)	VAS; ODI	B; 1,3,6,12m	VAS reduced: Back 40%, Leg 50%; ODI 25% better

HRQoL=primary health related quality of life outcome measure; VAS=visual analogue pain scale; MODEMS= Musculoskeletal Outcomes Data Evaluation and Management System; ODI=Oswestry Disability Index; OA=Osteoarthritis; ZCQ=Zurich Claudication Index; PCS=Physical conditioning scale SF-36; MCS=Mental conditioning scale SF-36; B=Preoperative baseline; Further surgery=lumbar region; SS=symptom severity domain of the ZCQ; PF=physical function domain of the ZCQ

X-Stop: Of the four ISP implants discussed in this review, the X-Stop appears to have been the most thoroughly investigated, both from a clinical and biomechanical perspective. Clinical investigations have focussed on patients with neurogenic intermittent claudication as a consequence of lumbar stenosis. Follow-up studies from one to four years (Zucherman et al. 2004; Zucherman et al. 2005a; Hsu et al. 2006; Kondrashov et al. 2006) have all reported improvement in pain and condition-specific function in this clinical population. The primary indication for use of the X-Stop implant is symptomatic lumbar stenosis, improved with lumbar flexion (Christie et al. 2005).

Coflex: Few published investigations are available for the Coflex implant. Clinical support for the use of this device has been reported in individuals with degenerative spinal stenosis (Kong et al. 2007). A recent investigation has questioned its efficacy as an augmentation to decompressive surgery in the treatment of lumbar spinal stenosis (Richter et al. 2010).

A summary of registered clinical trials investigating interspinous implants is provided in Table 2.4.

2.6.5 Discussion of ISP-related literature

Design characteristics of various ISP implants have been summarised, with a focus on the DIAM, Wallis, X-Stop and Coflex devices. Investigations describing these four examples represent the main published literature supporting the use of such devices in the treatment of lumbar degenerative disorders. The DIAM, Wallis, X-Stop and Coflex implants arguably stand as second generation devices borne from the first silicone-based interspinous spacer that originated in the early 1990s (Minns and Walsh 1997). The varied primary materials and surgical approaches employed in the design of these four implants (Table 2.1), has preceded an apparent move toward the use of PEEK as the primary implant material, alongside a less invasive implanting technique described for the next generation of interspinous devices (Table 2.2). Compared to laminectomy, implanting an X-Stop device was reported to represent a less-invasive, more economical surgery (Hannibal et al. 2006). When results are ultimately reported for clinical trials investigating the safety and efficacy of the newer devices (Table 2.4), any potential benefits of the contemporary, less-invasive designs may be better appreciated. Whether any developments allow for an increased utility in patient-groups that would be deemed inappropriate for more invasive surgeries, is a question that may have relevance in the increasingly aging populations to which they are currently applied.

Results of the only study comparing the DIAM, Wallis, X-Stop and Coflex implants revealed similar biomechanical effects of all four implants on cadaveric spinal mobility, despite differences in their design characteristics (Wilke et al. 2008). This may provide support for applying mobility results obtained for one device to all interspinous implants. Whether similarities found in testing cadaveric spines has a broader application to encompass the in vivo environment, is a relationship worthy of cautious consideration. Published evidence exists for a mild reduction in segmental flexion-extension mobility after implantation with an interspinous device (Lindsey et al. 2003; Phillips et al. 2006; Siddiqui et al. 2006b; Wilke et al. 2008). The reduction may be smaller when applied clinically to cases with LSS (Siddiqui et al. 2006b). All implants appear to have a stabilising, motion-limiting effect in extension, with no effect on axial rotation (Lindsey et al. 2003; Phillips et al. 2006; Siddiqui et al. 2006b; Wilke et al. 2008). However, the effect an ISP implant has on flexion or lateral bending may depend on what device is used and how and by whom it is applied. Should the primary aim for surgery be centred on restoring segmental stability in all directions, use of an interspinous device may not represent the most suitable option. Improving stability or reducing motion into extension, without limiting other spinal ranges at the implanted segment, appears to represent the most likely beneficial mechanical effect imposed by an interspinous device. This should be considered in clinical decision-making.

Given the limitation to flexion-extension motion as discussed above, the results of Wiseman et al (2005), who showed reduced facet loading in extension in the presence of an ISP device in cadaveric segments, appear reasonable.

This is despite their clinically nonphysiological method, which involved removing facet joint capsules and ligamentous tissue, potentially increasing segmental range, in order to place the pressure-sensitive film. Their result may provide biomechanical support for the use of an ISP device in patients in whom facet joint approximation, particularly in extension, is the source of symptoms.

Central canal and foraminal stenosis represented the initial clinical conditions to which interspinous devices were applied (Christie et al. 2005). In support for the rationale behind their use in these cases, in-vivo investigations have shown increased central canal and foraminal area in subjects implanted with an interspinous device (Siddiqui et al. 2005; Siddiqui et al. 2006a,b). The increased area has been attributed to unbuckling of the ligamentum flavum and posterior disc anulus, as was originally hypothesised (Minns and Walsh 1997) (Figure 2.11). Interspinous implants were largely introduced for their perceived limited, if any, effect at adjacent levels, thereby offering a benefit over rigid fusion. Results of the two cadaveric investigations that have assessed this feature were equivocal. One showed no effect on intradiscal pressure above or below the implanted segment (Swanson et al. 2003), while the other indicated a $<1^{\circ}$ reduced motion at the segment below (Lindsey et al. 2003).

Table 2.4: Current clinical trials investigating interspinous implants that are registered with ClinicalTrials.gov (a service of the US National Institutes of Health). Details include the: device name, registration number, trial title, principal investigator, comparison group, estimated sample size, single or multi-group design, commencement and expected completion dates (mm/yy), stage of investigation, pain and function outcome measure inclusion criteria, and subject age range.

Device	#	Reg. Number	Trial Title	Investigator	Comparator	Sample	Group	Dates	Stage	VAS LS:Leg	Function	Ages
DIAM	1	NCT00627497	Safety & effectiveness of DIAM vs decompression	Medtronic	Decompression	26	Single	2/08 2/11	Terminated	>60	ODI>40	>35
	2	NCT00456378	Safety & effectiveness vs conservative care	Medtronic	Conservative	306	Multi	12/06 11/10	Recruiting	>60:>80	ODI>30	18-70
	3	NCT00749996	Herniectomy vs herniectomy + DIAM in complex DD	Medtronic	Herniectomy	268	Multi	11/06 12/11	Recruiting	>30:>60	ODI>34	20-60
Wallis	4	NCT00134537	Wallis mechanical normalisation system for LBP (DD)	Abbott Spine	Exercise and conservative	300	Multi	11/04 6/06	Ongoing	>30:+/-	ODI>30	18-60
	5	NCT00484458	Wallis for LBP	Abbott Spine	TDR	340	Multi	1/07 12/10	Ongoing	≥40	ODI≥40	18-60
X-Stop	6	NCT00558129	Effects of X-Stop vs laminectomy	Medtronic	Laminectomy	154	Multi	11/07 11/11	Withdrawn pre recruitment	-	ZCQ>2	>50
	7	NCT00534092	Long-term outcomes for LSS	Medtronic	n/a	75	-	12/06 9/10	Recruiting	-	ZCQ>2	>50
	8	NCT00546949	Treatment of LSS: decompression vs XStop	Norwegian UST	Decompression	180	-	3/07 12/10	Recruiting	N/R	ZCQ N/R	50-85
Coflex	9	NCT00534235	Coflex vs fusion to treat LSS	Paradigm Spine	Fusion	460	Multi	9/07 -	Recruiting	>50:	ODI>40	40-80
X-Stop[PK]	10	NCT00517751	Condition of approval	Medtronic	-	240	Single	8/07 8/14	Recruiting	-	ZCQ>2	>50

Superion	11	NCT00692276	Superion in LSS	VertiFlex	X-Stop	400	Multi	6/08	Recruiting	-	ZCQ;ODI	>45
								6/11				
InSpace	12	NCT00697827	InSpace in LSS	SynthesSpine	X-Stop	500	Multi	6/08	Recruiting	-	ZCQ>2	>50
								6/12				
NL Prow	13	NCT01053364	Feasibility in LSS	Non-Linear Technologies	-	6	Single	1/10	Recruiting	N/R	Walk test	N/R
								9/10 +1yr				
"Spacer"	14	NCT01057641	Percutaneous "Spacer" in LSS	University of Cologne	Best non-operative	22	Single	4/10	Not yet recruiting	-	SF36	>50
								4/11			ZCQ	

#=trial code for later thesis reference; NCT=clinicaltrials.gov identifier; LSS=lumbar spinal stenosis; DD=disc degeneration; LBP=low back pain; TDR=total disc replacement; VAS=visual analogue pain scale; LS=lumbar spine pain; Leg=leg pain; ODI=Oswestry Disability Index; ZCQ=Zurich Claudication Index; Single=single centre; Multi=multicentre; N/R=not recorded

Further fundamental investigations are required to better understand the effect on sagittal alignment that an interspinous device might have at adjacent or regional levels (Lindsey et al. 2003; Siddiqui et al. 2006b; Kim et al. 2007; Crawford et al. 2009b).

Their effect on healthy segments or those with varied pathologies may also be relevant. This should then be related to any potential clinical presentation or symptomology. Similarly, the purported effect of a segmental kyphosis at the implanted level has received somewhat tenuous support, with a single cadaveric study providing the only reasonable evidence for a 2˚ skeletal kyphotic tilt (Lindsey et al. 2003). Whether measurement tools employed to capture this detail have been sufficiently sensitive in determining small changes to intervertebral angles, is an important consideration. Identifying relationships that may exist between patient-reported outcomes and the biomechanical effect of surgery with an interspinous device would represent valuable additions to the literature.

Mounting clinical evidence exists for application of ISP devices in patients with lumbar spinal stenosis, with little describing their use in other lumbar pathologies. The potential for ISP implantation as an isolated surgical procedure exists; however they appear more commonly employed as an augmentation to other decompressive or fusion surgeries, and therefore their clinical effect when used in isolation remains poorly understood.

Despite evidence for the effectiveness of each device in improving patient self-reported pain and function, relevant clinical indications remain ill-defined. This arises from a lack of evidence that reports, through comparable outcome tools, (i) performance of the device in discreet lumbar pathologies or, (ii) comparison of its use in augmentation of decompressive or other surgeries or, (iii) its application in isolation.

Presently, lumbar spine pathologies that best respond to dynamic stabilisation with interspinous implants remain ill-defined. Biomechanical evidence as discussed above suggests a benefit in posterior element degeneration, and in particular in both foraminal and central canal stenosis. The most compelling medium-term evidence available is for the X-Stop device used in the treatment of individuals with neurogenic intermittent claudication secondary to spinal stenosis (Zucherman et al. 2004; Zucherman et al. 2005a; Hsu et al. 2006; Kondrashov et al. 2006). Studies that have included other indicated pathologies do not adequately detail their methodologies, thereby limiting the interpretation of their findings (Caserta et al. 2002; Schiavone and Pasquale 2003; Mariottini et al. 2005; Senegas et al. 2007; Taylor et al. 2007; Crawford et al. 2009a). Others have reported unsatisfactory re-operation or re-herniation rates than confer no clear advantages on the use of the interspinous implant over conventional surgery (Floman et al. 2007; Crawford et al. 2009a).

Spinal stenosis is a broad diagnosis potentially involving several clinical pathologies: central, foraminal, or both. The distinction between anterior or posterior canal compromises being due to different anatomical influences in central stenosis might be important information for a surgeon wanting to rationalise interspinous implant suitability. Similarly, the broad classification of disc degeneration might also be too encompassing to offer any value to clinicians rationalising their surgical choices. As such, the present research remains inadequate to properly indicate the most suitable device, or the most responsive spinal disease. Subject categorisation that is based on imaging pathology, perhaps triaging to indicate those from either the anterior, middle, or posterior column (Denis 1983), might represent a valuable addition to the current diagnostic focus. Long term follow-up assessments of larger, homogeneous cohorts with a single discreet diagnosis are necessary to provide indications and best practise guidelines.

Advantages over non-operative management have been identified for surgery using the X-Stop device in one investigation (Zucherman et al. 2005b). Whether surgery employing interspinous implant offers results superior to conventional decompressive surgeries like laminectomy essentially remains unanswered. Interspinous implants are routinely employed to augment other surgical techniques, thereby confusing the effect of each procedure used in isolation. Clinical trials designed to compare the outcomes of decompressive surgery alone, versus decompressive surgery augmented with an interspinous implant, would contribute to this body of knowledge. Table 2.4 indicates that investigations examining these aspects predominate the focus in contemporary clinical trials, and in particular, is currently underway for the DIAM and X-Stop devices. Additionally, outcomes after surgery employing some of the new devices (Table 2.2) are being compared with outcomes after X-Stop surgery (Table 2.4), which may identify benefits of the potentially less-invasive third generation implants.

Single-centre investigations may control for inter-surgeon variability; however that approach may limit the subject numbers required for adequate statistical power in examining discreet cohorts. Therefore, future studies should aim to recruit subjects from multiple centres, but with strictly standardised inclusion criteria and common outcome measures.

2.6.6 Summary

Surgery with interspinous implant continues to be an option in the treatment of lumbar pathologies, with several devices being promoted to offer clinical advantages and improved outcomes. This review has discussed the biomechanical and clinical evidence for the DIAM, Wallis, X-Stop and Coflex implants. New interspinous devices and future clinical trials have been introduced to represent the next generation and future directions for this surgery. Suggestions have been made for further investigations to improve the provision of clinical guidelines for interspinous implants in treating lumbar spine disease.

Part 3: OUTCOME ASSESSMENT IN LUMBAR SINE RESEARCH: MEASUREMENT SYSTEMS

2.7 Introduction

Selecting outcome measures for back pain research is a challenging step in the development of a sound study strategy. The multifaceted nature of back pain, with its complex physical, behavioural and psychological manifestations, ensures a difficult path to obtain concrete objective measures of severity and progression. The present study utilised a combination of assessment methods to determine clinical outcomes after lumbar surgery augmented with DIAM interspinous implant. Measurements included: Health-related quality of life (HRQoL), surveyed using a patient-reported questionnaire purpose-designed by the author based on established instruments; surface thoracolumbar curvature based on measurements sought from the use of video rasterstereography; and skeletal lumbar curvature as determined from erect lateral plain lumbar radiography. Part III of this chapter will review these measurement systems as they relate to the assessment of clinical outcomes for the cohort being followed in this investigation.

2.8 Health-related quality of life (HRQoL) assessment

2.8.1 Introduction

Several HRQoL instruments have been developed to fulfil the requirement for dependable outcome measures in epidemiological and clinical research into low back pain. Patient-reported instruments provide the patients perspective on treatment effectiveness, which has become an important source of low back pain endpoint data (Beaton 2000). The trend toward the use of patient-reported outcomes (PROs) over more traditional clinician-derived physiologic records, is based on their superior reproducibility and validity (Deyo 2001). Patient-based outcome instruments are considered the most important tool clinicians, patients, researchers and policymakers can use to learn about the effectiveness of various interventions (Bombardier 2000).

The literature reporting the use of HRQoL questionnaires relating to back pain research is extensive. A broad and encompassing coverage of all available tools is beyond the scope of this section, which will instead focus on reviewing the basis for the measurement instruments selected for use in this study. A historical basis for the early development of HRQoL patient-based questionnaires is initially described and followed with separate attention to the measurement instruments forming the basis for patient-based questionnaires employed in the retrospective and prospective phases of the investigation.

2.8.2 Historical basis

In order to quantify an individuals HRQoL at their baseline and in response to treatment, all 'health' domains, including symptoms, functional status, general well being, disability and satisfaction, should be assessed (Deyo et al. 1998; Bombardier 2000). A wide choice of questionnaires designed to capture this detail grew by the 1990s, leading to a confusing choice for researchers (Bombardier 2000). In response, international experts in the study of back pain collaborated to review and recommend a standardised tool (Deyo et al. 1998). A six-item core set of questions (Table 2.5) was initially proposed to provide sufficient utility for use in quality improvement in clinical settings and for more formal research. Questions were derived from existing measures in common clinical use (Patrick et al. 1995; Atlas et al. 1996; Cherkin et al. 1996), with responses considered individually to reduce the risk of obscuring change in the separate health domains (Deyo et al. 1998; Deyo 2001). Success in delivering reliable, valid and responsive information in a time- and cost-effective way is a strong feature of the core set, which has continued to receive support in outcome measurement in low back pain (Mannion et al. 2005a, 2009a,b; Ferrer et al. 2006). Symptom specific items (pain & function) are known to be more responsive than generic items (well-being & work disability) (Mannion et al. 2005a).

Table 2.5: 'Core set' questions for outcome assessment in patients with back pain according to Deyo and Battie et al (1998).

Domain	Specific Questions	Source
Pain symptoms	During the past week, how bothersome have the following symptoms been? a) low back pain b) leg pain (sciatica) or Visual analogue pain scale (VAS)	From back pain PORT (Patrick et al. 1995; Atlas et al. 1996)
Function	During the past week, how much did pain interfere with your normal work (including both work outside the home and housework?	SF-36 and SF-12 (Ware 2000)
Well-being	If you had to spend the rest of your life with the symptoms you have right now, how would you feel about it?	From back pain PORT (Cherkin et al. 1996; WHOQOL-group 1998a,b)
Disability	During the past 4 weeks, about how many days did you cut down on the things you usually do for more than half of the day because of back pain or leg pain (sciatica)?	Adapted from questions in NHIS (Patrick et al. 1995)
Disability (social role)	During the past 4 weeks, how many days did back pain or leg pain (sciatica) keep you from going to work or school?	(Roland and Morris 1983)
Satisfaction with care	During the course of treatment for your low back or leg pain (sciatica), how would you rate your overall medical care?	

PORT=Patient Outcomes Treatment Trial; SF-36= MOS Short-Form 36; NHIS=National Health Insurance Survey

Deyo and colleagues promoted an expanded outcome set (refer to Table 2.6) aimed at providing improved precision for research to facilitate a scientific advance in clinical care (Deyo et al. 1998). Further revisions to this set were detailed in a focus issue of Spine where each component was elaborated by leading commentators for each included measure (Fairbank and Pynsent 2000; Kopec 2000; Lurie 2000; Roland and Fairbank 2000; Ware 2000).

Table 2.6: Expanded set of patient-based outcome measures for use in spinal disorder research (modified from Deyo, Battie et al 1998).

Domain	Instrument	Items	Score
Pain symptoms	Frequency or bothersomeness of low back or leg (sciatica) pain, or VAS (back & leg)	2 (5 levels)	1 – 5
Back specific function	Roland-Morris (RMQ) (or adaptations) or Oswestry (ODI) (or adaptations)	24 (yes/no) 10 (6 levels)	0 - 24 0 - 100
Generic health status	SF-12, EuroQol or SF-36 And "if you had to spend the rest of your life with the symptoms you have right now, how would you feel about it?"	12-36 (variable) 1 (5 levels)	8 dimensions: 100 – 0 each, or norm-based: mean50; SD10
Work disability	Days of work absenteeism Days of cut down activities Days of bed rest	No of days No of days No of days	Nominal scale
Satisfaction: back specific	Single question on overall satisfaction	1 (7 levels)	1 – 7

Comparisons between data derived from individual physicians, clinics, hospitals or patient cohorts due to demographic or clinical differences were cautioned (Deyo 2001). This outline of measures forms the cornerstone to a majority of back pain research performed today.

To allow for comparisons to existing literature, outcome measures selected by peers in reporting the use of interspinous implants in the treatment of lumbar spine disease were of interest. Table 2.7 presents measurement instruments employed in key published papers to describe the clinical outcomes after surgery involving either the DIAM or other interspinous implants.

<u>2.8.3 Phase I - Retrospective study arm</u>

The Musculoskeletal Outcomes Data Evaluation and Management System (MODEMS) Lumbar Spine Instrument (LSI) was the primary outcome tool already in use by the collaborating neurosurgeon (QM) involved with the present research and thesis. Data derived from these questionnaires that were prospectively completed by previous patients of the surgeon, were audited, reviewed and reported as a first-stage component of this project (Crawford et al. 2009a). Aspects of the MODEMS LSI are outlined to follow. MODEMS was developed as a quality improvement effort by a collaboration between the American Academy of Orthopaedic Surgeons (AAOS), the North American Spine Society (NASS), the Scoliosis Research Society

(SRS), the Cervical Spine Research Society (CSRS), the Orthopaedic Rehabilitation Association (ORA), the American Spinal Injury Association (ASIA) and the Council of Spine Societies (CSS) (Deyo 2001). The LSI, specifically designed for use in back pain research, was one of 11 collections developed to assess outcomes of various musculoskeletal conditions. MODEMS-LSI was subject to copyright in 1997, with version 2.0 published in 1998 (Walsh et al. 2003). The later version was employed in this study.

Table 2.7**:** Summary of the HRQoL and imaging outcome measures employed in clinical trials reporting on lumbar surgery with interspinous implant. This indicates a predominant use of VAS to describe pain and ODI to describe function.

Author, Year	**ISP**	**Patient cohort**	**Outcome Measures**
Cabraja et al, 2009	Coflex	Facet Joint Syndrome	VAS; ODI; Radiography
Kuchta et al, 2009	X-Stop	LSS with NIC	VAS (leg); ODI; MRI
Sobottke et al, 2009	X-Stop Wallis DIAM	LSS	VAS; Radiographic
Brussee et al, 2008	X-Stop	LSS	SF-36; Zurich Q
Floman et al, 2007	Wallis	Disc herniation	VAS; ODI; SF-36
Kim et al, 2007	DIAM	LSS; recurrent or large disc herniation	VAS (back & leg); Radiographic
Kong et al, 2007	Coflex	LSS	VAS; ODI; Radiography
Taylor et al, 2007	DIAM	LSS (foraminal & soft); Disc: herniation, bulge, disease	Dallas Pain Q; Incidence data
Kondrashov et al, 2006	X-Stop	LSS	ODI

VAS=Visual analogue scale; ODI=Oswestry disability index; LSS=Lumbar spinal stenosis; NIC=neurogenic intermittent claudication; SF-36=Short-form 36; Q=Questionnaire

MODEMS-LSI represents a collection of 62 questions aimed to capture patient health status with a primary focus on back pain. A mappable body chart is used alongside questions to identify co-morbidities (questions 4-17), a complete SF-36 for general health status (questions 18-28), treatment history and satisfaction questions (29-37), pain frequency (questions 38-41), pain severity/bothersomeness (questions 42-45), nine questions (46-54) modified from the Oswestry Disability Index (ODI; (Fairbank and Pynsent 2000)) to measure back-specific function, and demographic questions (55-62) (Daltroy et al. 1996). Normative population data was assessed for this instrument in the United States to facilitate subpopulation comparisons (Hunsaker et al. 2002). Tests for reliability and validity were favourable for its English, German, Italian, Spanish and computerised forms (Daltroy et al. 1996; Pose et al. 1999; Padua et al. 2001; Peters et al. 2004; Sarasqueta et al. 2005; Schaeren et al. 2005). The sum of patient responses to 11 questions including: the frequency (38) and severity (42) of back pain, and the nine ODI-based questions (46-54), are divided into the maximum possible score for these questions (66). This yields a percentage (0-100) referred to as the MODEMS Pain and Disability Lumbar scale (MPDL) (Walsh et al. 2003). A back and leg pain scale can be derived from four questions regarding the frequency (38, 39) and bothersomeness (42, 43) of back and leg pain, also presented as a percentage (Walsh et al. 2003). The nine ODI-based questions may be considered on their own to represent back-related function. These latter two measures were used alongside a single question regarding patient satisfaction with their current status, and a further question relating to medication use, for the Phase I component of the current investigation (Crawford et al. 2009a).

2.8.4 Phase II - Prospective study

Primarily based on the recommendations outlined in Tables 2.5 and 2.6, it was felt that a questionnaire for use in the prospective component of this study should include questions that captured all health domains. Of significance for use in this clinical trial was minimising subject burden in attempts to maximise responder compliance. The arguably cumbersome 62-question MODEMS LSI was rejected in preference for one with fewer questions that required less time to complete and that offered a similar measure of health. A self-report, condition-specific questionnaire was therefore developed for use in the prospective trial of this project (Appendix V). Key recommended outcome tools according to each health domain that are relevant to the formation of the questionnaire used for this study, and therefore this thesis, are reviewed.

Pain Symptoms: A commonly reported measurement instrument used in capturing pain symptoms in health-related research is the Visual Analogue Scale (VAS). VAS provides a linear measurement of a patient's pain perception by employing a 10cm line anchored by two pain extremes (e.g. 'No pain' to 'pain as severe as possible') (Jensen et al. 1986). The patient is required to mark the line along its continuum to indicate their perceived discomfort. The distance from the 'no pain' end to the patient's mark is measured and presented as a percentage.

Utility of pain intensity scales are judged on a combination of their: ease of administration; rates of correct response; sensitivity through response number; sensitivity in detecting treatment effect; and their relationship to a superior combined measure of subjective pain intensity (Jensen et al. 1986). VASs have been criticised for requiring written completion, a second stage for error introduction in necessitating the rater's measurement of the patient's line, and widespread use of photocopies to apply the instrument, which can alter line-length and therefore precision between trials (Jensen et al. 1986). Older patients (age~75yrs) are shown to have more difficulty using the VAS compared to those who are younger (age~55yrs) (Kremer et al. 1981; Jensen et al. 1986).

Back-specific Function: Instruments for evaluating functional status include generic and disease-specific measures, with the latter an advantage in focussing on the ability to perform tasks that are unique to the specified condition (Deyo et al. 1998; Bombardier 2000; Lurie 2000). Despite a wealth of literature reviewing and testing outcome measures for back specific function, there appears to be few reports of direct comparisons between measures across similar populations (Kopec 2000). As such, statements regarding superiority cannot be confidently made (Bombardier 2000). In reviewing ten condition-specific back function measures, Kopec (2000) described the Roland-Morris Disability Questionnaire (RMDQ) and Oswestry Disability Index (ODI) to be the most valid self-report functional status tests specific to back pain. Their clinical utility has been extensively tested, with both now well-accepted for use assessing the progress of patients with low back pain in a variety of clinical and research settings (Roland and Fairbank 2000). RMDQ is believed to better discriminate in measuring patients with mild to moderate disability, with the ODI favoured for those with persistent severe disability (Deyo et al. 1998; Roland and Fairbank 2000). Either scale has been included as recommended outcome tools for use in clinical back pain research (Table 2.6), with the choice between the two dependent on the patient cohort being studied (Deyo et al. 1998). Given the prospective arm of this study follows patients being surgically treated for their back pain, persistent severe disability was assumed and therefore the ODI was considered most appropriate.

Oswestry Disability Index (ODI): The ODI is a low back-specific questionnaire that clinically assesses the disabling effects of low back pain, expressing an estimate of disability as a percentage score where higher scores indicate the greatest dysfunction (Fairbank et al. 1980). Ten items assess pain, personal care, lifting, walking, sitting, standing, sleeping, sex life, social life and travelling (Fairbank et al. 1980). The recent versions (v2.0 and v2.1a) which require respondents to answer the questions in relation to how their back problem affects them 'today' are preferred (Fairbank and Pynsent 2000). Hanscom et al (2002) revealed notably higher missing response rates for the paper and computer-based forms of the ODI compared to the SF-36 as a result of the ODI question pertaining to sex life. Rather than exclude this question we proposed the addition of a response "question not relevant to my circumstances" so as to improve response rate and allow for its exclusion (if necessary) in the data analysis.

Generic Health Status/Well-being: Based on the expert recommendations that were outlined in Tables 2.III.2.1 and 2.III.2.2, the author felt the decision for inclusion in the compiled HRQoL survey was between a singular use of the 'core' question: "If you had to spend the rest of your life with the symptoms you have right now, how would you feel about it?" or the Medical Outcomes Trust Short Form 36 (SF-36) generic health outcomes tool (Deyo et al. 1998; Bombardier 2000; Ware 2000). The latter originated out of instruments that have been in use since the 1970's (Ware 2000) and as such the SF-36 has been documented in over 1000 publications, having been widely tested and positively reported (Bombardier 2000). The SF-36 comprises 36 questions that can be aggregated into two summary measures: physical and mental health (Bombardier 2000; Ware 2000). Ware (2000) reports that physical functioning, role-physical and bodily pain scales correlate highly with the PCS and are most responsive to treatments that change physical morbidity. This has been confirmed in a study assessing lumbar spine diagnoses (Pahl et al. 2006). Some contemporary authors in back pain research have preferred to use select components of the SF-36, most commonly the bodily pain and physical function scales, to reflect clinical improvements in their patient cohort (Swan et al. 2006; Weinstein et al. 2006). The full SF-36 is claimed to have superior measurement properties over the abbreviated SF-12 and is preferred for measuring change in the clinical context, with version 2.0 being promoted over its predecessor (Ware 2000). The SF-36® Health Survey is a licensed product (Medical Outcomes Trust, Massachusetts, USA, 1992).

The single question in the original 'core set' recommended by Deyo et al (1998) and outlined earlier, is measured via a 5-level Likert scale where the available responses are: very dissatisfied, dissatisfied, neutral, satisfied or very satisfied. A recent investigation has shown that the type of health-survey used, either generic or condition-specific, may be less important than the need to control and assess for existing psychosocial and medical comorbidities (Slover et al. 2006). Concerned that patient compliance may decline if a long questionnaire was administered (Edwards et al. 2002), and with reference to the presented literature review, the main investigation favoured the use of the ODI as a measure of function and the single 'core' question as an indicator of general well-being.

Minimally important difference (MID): Statistical significance does not necessarily infer change that is clinically meaningful (Wright 1996). Defining what constitutes a change of clinical importance in back pain has been the subject of debate and expert panel discussions for over a decade (Deyo et al. 1998; Bombardier 2000; Ostelo et al. 2008). Understanding the meaning of differences observed in longitudinal studies requires an appreciation of the minimal clinically important difference (MCID) (Jaeschke et al. 1989). MCID originally included change that was reported by patients as "almost the same, hardly any better/worse" (Jaeschke et al. 1989). More recently, the term minimally important difference (MID) is defined as "the smallest difference in score in the domain of interest that the patient's perceive as important, either beneficial or harmful, and that would lead the clinician to consider a change in the patient's management" (Guyatt et al. 2002).

Factors that may influence MID interpretation include: whether change is reported using distribution or anchor-based methods (Lydick and Epstein 1993); whether different interventions (like surgery and conservative treatments) are being compared (Hagg et al. 2003), and; whether group or individual change (Guyatt 2000) is of importance to the investigator.

Reporting the results of the most recent IMMPACT [Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials] meeting, Dworkin et al (2008) outline other considerations for anchor-based methods to include: absolute versus relative (to baseline) change, patient's baseline status (or magnitude of symptoms), patient characteristics (age, sex, education and their specific clinical condition), whether improvement or worsening is being considered, minimally detectable or important clinical change, and whose opinion constitutes the primary emphasis, patient or clinician. Recommendations for standardised MID values (applicable to commonly used outcome instruments) have been recently revised in order to assist in interpreting change score data (Dworkin et al. 2008; Ostelo et al. 2008). MID values are outlined separately below for the pain and function variables used in the present study.

VAS: For chronic pain conditions, Dworkin et al (2008) indicate that: pain reductions in individuals between 10-20% suggest minimal or little change, while change in excess of 30% is more meaningful to patients, reflecting moderate improvement. They also indicate that change of 50% or more reflects substantial improvement suggestive of a high response (Dworkin et al. 2008). These guidelines generally agree with MID values described by experts investigating low back pain specifically (Ostelo et al. 2008). Ostelo et al report the MID range for absolute change to be 15-20%, and 20-30% for improvements referencing baseline values.

ODI: MID in ODI scores has been estimated by different observers to range between 4 and 17% (Taylor et al. 1999). The U.S. Food and Drug Administration (FDA) has recommended a minimum reduction of 15% between pre- and post-operative time-points after spinal fusion (Fairbank and Pynsent 2000). Experts recently revising the interpretation of low back pain change scores have defined the MID for ODI between 10-12% for absolute change, and between 20-30% improvement from baseline (Ostelo et al. 2008).

Missed data: Attrition represents one of the main methodological problems with observational longitudinal studies and tends to occur toward the end of the period of follow-up and for various reasons (Twisk and deVente 2002). The appropriate treatment of missing repeat measures data continues to be a contentious issue about which several opinions exist (Norris et al. 2000; Shih 2002; Twisk and deVente 2002; Shao and Zhong 2003; Elliott and Hawthorne 2005; Huang and Carriere 2006). Summarising all available methods is beyond the scope of this review, which instead focuses on the last-value-carried-forward (LVCF) imputation method that was recommended for use in the present study on consultation with a leading statistician at the author's academic institution (Knuiman 2008).

The LVCF is an accepted method for missed time-point data where single imputation is appropriate (Twisk and deVente 2002; Shao and Zhong 2003; Knuiman 2008). Alternative methods including imputing the data of the closest matched case to the subject with missing data (Elliott and Hawthorne 2005), or the mean of the time-point data obtained before and after the missed value (Twisk and deVente 2002; Huang and Carriere 2006), were considered less applicable for the present study based on data availability. The LVCF method is an effective method for drop-out and missed time-point data however 'failed' cases may present bias where the trend for carrying forward high observations is predictable (Twisk and deVente 2002; Elliott and Hawthorne 2005; Huang and Carriere 2006).

To better appreciate the consensus opinion regarding the treatment of missing data in spine research, methodologies of selected landmark clinical papers were reviewed. Some authors did not declare their missed data treatment methods (Fritzell et al. 2001; Swan et al. 2006); one broadly referred to intention-to-treat analysis (Carragee 2006); one used multiple imputation and ANCOVA (Fairbank et al. 2005); while the SPORT trials employed the single imputation methods of baseline and LVCF, as well as a mixed model controlling for covariates (Weinstein et al. 2008a; Weinstein et al. 2008c). Outcomes data using models with and without mean substitution imputation were compared in examining the surgical treatment of lumbar spinal stenosis, with no differences found (Katz et al. 1997). One investigation assessing clinical outcomes after ISP implant surgery broadly referred to employing an intention-to-treat analysis in their randomised prospective study (Hsu et al. 2006). However, like all other ISP-related literature reviewed during the course of this thesis investigation, Hsu et al did not define their methods for treating missed data.

2.8.5 Summary:

Historical and contemporary aspects of HRQoL assessment using patient-reported questionnaires have been described. Outcome tools to measure pain and function are emphasised in relation to the retrospective and prospective phases (I&II) of the main investigation, which sought to examine health in DIAM-augmented surgery cases.

2.9 Surface spinal curvature assessment

2.9.1 Introduction

Numerous non-invasive instruments that differ in cost, portability and sophistication, have been developed for the quantification of surface lumbar curvature. Skin contact (tactile) methods that allow for the derivation of two-dimensional (2D) data include the: contour body tracer (Thulborne and Gillespie 1976), spinal pantograph (Willner 1981), flexible curve (or flexirule) (Burton 1986; Tillotson and Burton 1991), Debrunner's kyphometer (Ohlen et al. 1989), inclinometer (Mellin 1986) and clinometer (Bullock et al. 1987). The Metrecom electromechanical digitiser (Norton et al. 2002) and Spinal Mouse (Mannion et al. 2004) with their tri-planar 3D capacities, represent modern advances in tactile devices. These methods have been used to provide normative values for surface spinal curvature for comparisons within and between populations. Table 2.8 reports from the literature, variation of standing surface lumbar lordosis (SLL) values achieved through different measurement devices which involve skin contact. Resultant surface angular values are expressed in degrees similar to Cobb-based skeletal curvature (Cobb 1948; Harrison et al. 2001), with different tangent and trigonometric models applied to derive data (Youdas et al. 1995; Norton et al. 2002). Figure 2.12 illustrates a selection of manual instruments used to measure spinal curvature from the skin surface.

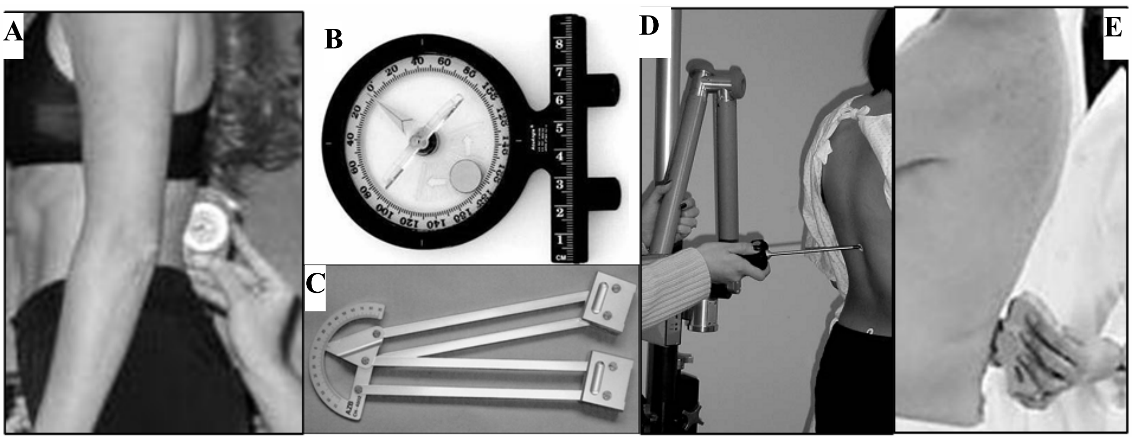


Figure 2.12: Non-invasive devices used for manual assessment of surface spinal curvature**.** [A] An inclinometer in use for lumbar assessment. [B] Baseline® AcuAngle inclinometer (retrieved January 2010; http://www.komkare.com/diagnostics/gonio_inclin/inclin_acu.html). [C] A modified Debrunner kyphometer (Korovessis et al 2001). [D] The Metrecom, an electrogoniometer based on the spinal pantograph (adapted from Norton et al. 2004). [E] The Spinal Mouse, a manual device capable of 3D assessment (adapted from Mannion et al. 2004).

Figure 2.13 outlines the tangent and trigonometric methods for characterising lumbar curvature from output derived employing these devices. The tangent method has been shown to underestimate trigonometric-derived values by approximately 12°; with inclinometer-based measurements being similar to those obtained using the tangent method (Norton et al. 2002). The trigonometric method implies a circular arc to the curve (Youdas et al. 1995).

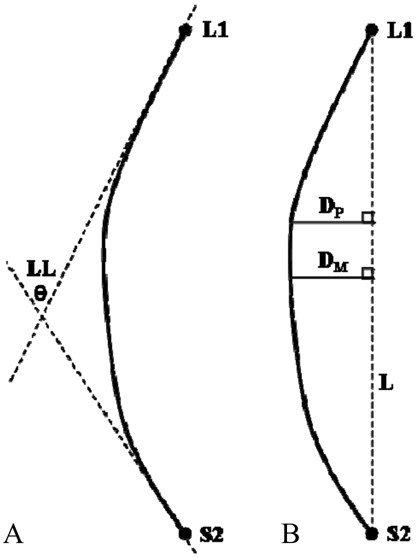


Figure 2.13: An illustration of the tangent [A] and trigonometric [B] methods for characterising lumbar lordosis (LLθ) based on the surface spinal contour plotted between L1 and S2 spinous processes using manual instruments (solid line). The trigonometric method calculates LLθ as a function of the length (L) between the L1 and S2 marked points, and the depth of the curve, which can be measured at its peak (DP) or where the length is bisected (DM), depending on researcher requirements. The formula used is: LLθ=4x [arc tan (2D/L)].

Table 2.8: Summary of ten studies that employed manual devices to estimate standing lumbar lordosis (LL) in adults without low back pain. Gender, age and instrument differences between the studies are highlighted.

Study	**Measurement Device**	**Subjects**					LL	
			Age			Gender*		
		n	Mean	SD	Range		Mean	SD
Youdas et al, 2006	Flexible curve	235	n/a	n/a	20-79	Male (119)* Female (116)	43.0 49.5	10.7 10.7
Mannion et al, 2004	Spinal Mouse	20	41	12	n/a	Male (9) Female (11)	32.0	7.5
Norton et al, 2004	Metrecom	60	39.3	n/a	n/a	Male (27)* Female (33)	33.7 45.6	11.5 15.2
Nourbakhsh & Arab, 2002	Flexible curve	300	n/a	n/a	20-65	Male (150) Female (150)	35.0	13.0
Ng et al, 2001	Inclinometer	35	29.9	7.3	n/a	Male (35)	24.0	8.0
Youdas et al, 1996	Flexible curve	90	54.8	8.7	40-69	Male (45)* Female (45)	37.5 52.7	11.0 15.3
Hultman et al, 1991	Debrunner's kyphometer	38	50.2	3	n/a	Male	27.1	7.4
Link et al, 1990	Flexible curve	61	25.2	2.5	n/a	Male	34.3	9.9
Ohlen et al, 1989	Debrunner's kyphometer	31	32	11	16-61	Male (10) Female (21)	32.0	11.0
Mellin, 1986	Myrin inclinometer	25	31.3	5.8	n/a	Male (9) Female (16)	23.0	8.0

n=subject number; SD=standard deviation; SLL=standing lumbar lordosis; n/a=not available; *indicates studies where female subjects had a significantly larger SLL than men ($p<0.05$)

Early tools were developed as clinically useful alternatives to plain film radiography, in order to indicate curvature change in progressive spinal diseases like adolescent idiopathic scoliosis. These methods were considered preferable as evidence suggested an increased risk of breast cancer in young women exposed to serial radiography (Levy et al. 1996; Goldberg 1998). A further advantage is the ability to assess important cosmetic factors like the rib hump (Theologis et al. 1993), which cannot be achieved from measurements based on standard plain radiographs. Measurement of this scoliotic feature had previously been achieved through computed tomography (CT); however such imaging delivers a higher dose of ionising radiation (Bearcroft 2007) than plain radiography.

Early instruments were limited to recording curvature in either the coronal or sagittal planes in two dimensions (2D), and therefore were subject to variability when assessing the anatomically complex three-dimensional (3D) posture. The development of more sophisticated 3D imaging methods improved the capture of spatial back shape information. The advent of computer-based systems has allowed for 3D computation of spinal curvature via methods involving: direct patient skin contact [the spinal mouse (Mannion et al. 2004); Ortelius800™ (a finger-tip operated spinous process sensor) (Ovadia et al. 2007); MicroScribe 3DX digitiser (a pantograph equivalent) (Van Schaik et al. 2002)] or optical methods such as Moiré topography (Adair et al. 1977) and structured light techniques [Integrated Shape Imaging System (ISIS; Oxford Metric Ltd, Oxford, UK) (Turner-Smith 1988) and its improved version the ISIS2 (Berryman et al. 2008); Quantec System (Quantec Image Processing Ltd, Lancashire, UK) (Wojcik et al. 1994); and video rasterstereography (Drerup and Hierholzer 1994)].

Despite a prevalent clinical use of body surface assessment tools, few investigators have tested the equivalence of devices or their canonical mathematical approaches (Salisbury and Porter 1987; Tillotson and Burton 1991; Youdas et al. 1995; Norton et al. 2002). Two studies comparing non-invasive methods for measuring lumbar curvature in flexion-extension (Tillotson and Burton 1991) and in static standing (Norton et al. 2002) concluded that the measurements from different devices were not interchangeable. Both studies signify the superiority of computer-interfaced shape data over that derived from an inclinometer. Salisbury and Porter (1987) and Youdas et al (1995) reported similar results when using the flexirule and inclinometer referencing the same end-points, indicating a preference for the clinical utility of the tangent method in deriving regional lordosis. Gangnet et al (2006) found significant differences in spinal and pelvic alignment values obtained through 2D (single plane) or 3D (biplanar) radiographic methods assessing 34 asymptomatic cases with no history of back pain (Gangnet et al. 2006). Although their study reports on skeletal variables, the differences noted between 2D and 3D measurement methods are relevant to the present investigation. The 3D topographical method of video rasterstereography is explained further below.

<u>2.9.2 Video rasterstereography:</u> Rasterstereography (Jenoptik Formetric, Aesculap Meditec GmbH, Germany) is a photogrammetric-based method for deriving 3D surface curvature of the thoracolumbosacral spine (Drerup 1982; Frobin and Hierholzer 1983). The system consists of

projector and video camera incorporated into a height-adjustable vertical unit that is mounted on a mobile base. The levelness of the base can be manually adjusted by referencing integrated spirit levels. Topographical grid lines are projected posteriorly on the subjects back. Segmental reconstruction is then used to produce a 3D image of vertebral curvature (Drerup 1982; Frobin and Hierholzer 1983). Frontal and sagittal projections of the symmetry line of the back are derived, allowing for computation of scoliotic, kyphotic and lordotic curve angles, in addition to trunk and pelvic inclination angles with respect to the vertical (Drerup and Hierholzer 1987b). The vertebral prominens and three pelvic region iliac processes are automatically identified and related to other features of the surface contour including bilateral axillae and body surface edges (Drerup 1982; Frobin and Hierholzer 1983). Rasterstereographic measurements of spinal curvature are determined through a segmentation process which assumes relative left and right symmetry (Drerup and Hierholzer 1987b). Shape analysis reports a 2D sagittal profile including lateral projection, inclination and curvature for the thoracolumbar spine via mathematical modelling. Tangents between three curvature inflexion points [cervicothoracic (ICT), thoracolumbar (ITL), and lumbosacral (ILS)] define kyphotic and lordotic apexes. Trunk and pelvic inclinations are identified with reference to the vertical. Key features of the rasterstereographic evaluation of back sagittal profile are illustrated in Figure 2.14. Methods for deriving specific variables of interest in this study are outlined later in Chapter 3.

Further to the non-invasive benefits of rasterstereography, its high resolution affords time-efficient automated acquisition and computerized processing of complex postural data (Drerup and Hierholzer 1994). The need for manual detection of anatomical landmarks is avoided with the systems high accuracy in automatic landmark localisation and subsequent reconstruction of surface data-points (Drerup and Hierholzer 1987b). Resultant landmark localisation that is based on the mid-sagittal line is reported to be independent of patient position and insensitive to postural changes and moderate asymmetry of the subject (Drerup and Hierholzer 1987b).

2.9.3 Rasterstereography system reliability:

The system reproducibility of a single rasterstereography-derived regional kyphotic or lordotic angle is reported by the system developers to be 2.8˚, while inclination measurements are expected to be within 2˚ (Drerup 1982).

System accuracy has been described for rasterstereography in clinical investigations following patients with idiopathic scoliosis (Drerup and Hierholzer 1987b; Hackenberg et al. 2003; Hackenberg et al. 2006), osteoporotic thoracic kyphosis (Goh et al. 1999b; Goh et al. 2000), and healthy volunteers (Lippold et al. 2006a; Crawford et al. 2009b) versus lumbar surgery adult populations (Crawford et al. 2009b). Rasterstereographic assessment of back shape generally has less variability [ICC=0.98-0.99; (Goh et al. 1999b)] in comparison with the flexirule

[ICC=0.78-0.98; (Milne and Lauder 1974; Lundon et al. 1998)], kyphometer [ICC=0.89-0.99; (Ohlen et al. 1989; Lundon et al. 1998)], radiography via the Cobb [ICC=0.81 to 0.99; (Lundon et al. 1998; Goh et al. 2000; Harrison et al. 2001)]or other computer-assisted methods [ICC=0.95; (Goh et al. 2000)].

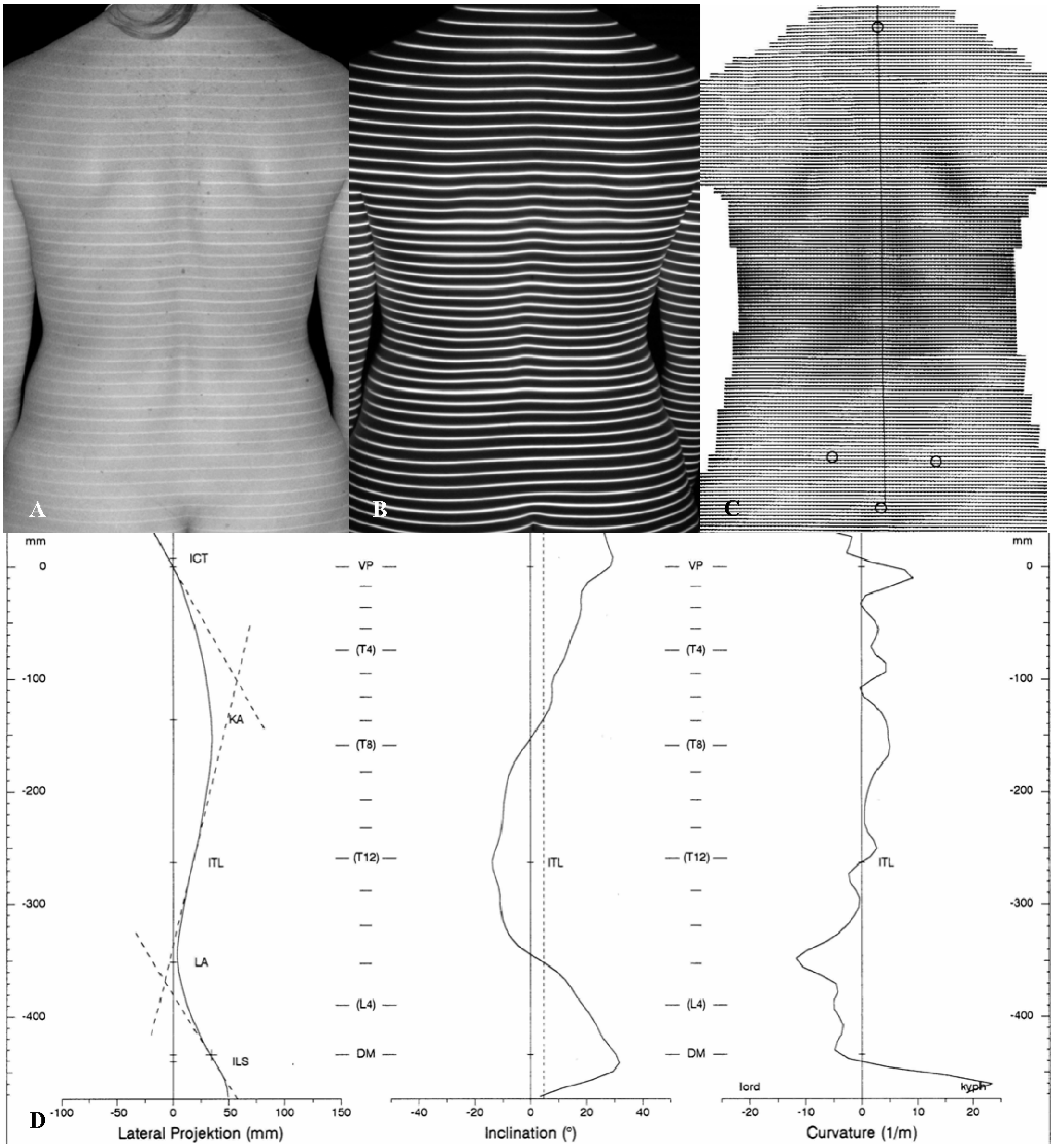


Figure 2.14: Key features of the rasterstereographic evaluation of sagittal profile for a standing 38 year old healthy female volunteer [A]. Topographical gridlines are projected onto the back surface [B]. Resultant transverse profile derived from the reconstructed back image demonstrating anatomical landmarks (marked by small circles) and spinal midline [C]. [D] Shape analysis report printout of the sagittal profile including lateral projection (left), inclination (centred) and curvature (right) lines. These are derived from mathematical modelling for the thoracolumbar curvature and are scaled for trunk height according to computed vertebral level (vertical axes) and trunk inclination (horizontal axes) centred from the vertebral prominens (VP) to the dimple midline (DM). For the lateral projection report the cervicothoracic (ICT), thoracolumbar (ITL), and lumbosacral (ILS) inflexions define kyphotic (KA) and lordotic (LA) apexes.

2.9.4 Summary:

Rasterstereography, as employed in measuring serial surface spinal curvature, has been reviewed in relation to its use in the present study in assessing adult healthy volunteers and DIAM-augmented lumbar surgery cases.

2.10 Skeletal spinal curvature assessment: Radiography

2.10.1 Introduction:

Quantitative evaluation of skeletal curvature represents a well-established means of monitoring progression and treatment of spinal deformities against normative and pathological reference values. Assessing skeletal alignment has long been considered valuable in planning, monitoring and progressing surgical and other interventions aimed at lumbar degenerative disorders, and for establishing normative and pathological reference values (Vrtovec et al. 2009). Maintenance of the physiologic sagittal profile is reportedly a key objective in lumbar surgery, with a flattened lordosis (or relative kyphosis) known to increase low back pain and contribute to a poor post-operative outcome (O'Shaughnessy and Ondra 2007).

2.10.2 Measuring lumbar lordosis

Lumbar lordosis (LL) and thoracic kyphosis (TK) are considered important for the maintenance of spinal sagittal alignment (Berthonnaud et al. 2005; O'Shaughnessy and Ondra 2007; Lafage et al. 2008). Sagittal balance, which describes the relationship of vertebra to each other with respect to the sagittal vertical axis (SVA), is applicable in guiding the surgical treatment of various lumbar degenerative disorders like spondylolisthesis and idiopathic scoliosis (O'Shaughnessy and Ondra 2007; Labelle et al. 2008). Similarly, maintaining optimal LL is a key outcome of lumbar spinal fusion in preventing adjacent segment overload, and in treating or preventing flat back syndrome (Kumar et al. 2001; Gardocki et al. 2002). Relationships found between TK and LL, and LL and sacral inclination (SI), indicate a balancing or compensatory nature of the thoracolumbosacral spinal curve (Voutsinas and MacEwen 1986; Kumar et al. 2001; Gardocki et al. 2002). Despite the accepted importance, surgeons and investigators have yet to agree on a single technique for measuring regional spinal shape; with the use of digital 3D-capable instruments gaining popularity over the more commonly applied 2D imaging like plain radiography (Vrtovec et al. 2009). Summarising the full extent of literature reporting on skeletal outcomes in lumbar pathologies is beyond the scope of this review, which will instead concentrate on sagittal spinal curvature derived from 2D plain radiographic images based on the existing patient assessment protocol employed by the collaborating neurosurgeon.

Over time, several investigators have compared regional spinal curvature between asymptomatic and low back pain subjects in attempts to better understand and identify potential risk factors for lumbar degenerative disorders. When considered together, these investigations have been inconclusive in respect to the influence of back pain on static spinal shape in standing, although studies that do report a difference between the two groups indicate reduced LL in subjects with LBP. Table 2.9 summarises the results of ten studies comparing lumbar lordosis (and thoracic kyphosis in two studies) in subjects with asymptomatic or painful backs. Relative lumbar kyphosis is shown to be more disabling than normal or lordotic lumbar Cobb angles (Glassman et al. 2005b). Patients with lumbar disc herniation have been shown to evidence a more positive sagittal balance, reduced lumbar lordosis, and a more vertical sacrum than healthy subjects without back pain as assessed from whole spine standing radiographs (Endo et al. 2010).

Table 2.9: Summary of 10 studies comparing skeletal lumbar curvature as derived from lateral radiography between asymptomatic and low back pain cohorts. Variable population cohorts, measurement methods, statistical treatment and results between those with and without back pain are evident.

Study	**Participants**	**Method**	**Result**
Rajnics et al, 2002	French; LBP: MRI evidence of LDH (n=50); Controls (n=30)	LBP: Position NR; Controls: standing; Mod Cobb L1-L5	LL: LBP < Controls TK: ND
Tsuji et al, 2001	Japanese (50-85y) (n=489); LBP x1 episode in <3m (VAS)	Standing Mod Cobb L1-S1	LL: LBP < (4°) those without
Tuzun et al, 1999	Turkish; LBP>6m (n=50); LBP<6m (n=50); no pain (n=50)	Standing Mod Cobb L1*-S1	ND
Korovessis et al, 1999	Greek; LBP≥2m (n=120); Controls: age-matched (n=120)	Standing Cobb LL=T12-S1; TK=T4-T12	LL: LBP < Controls; TK LBP > Controls
Harrison et al, 1998	USA; LBP<6w (n=50); LBP>6w (n=50); Controls matched (age, ht, wt, gender) (n=50)	Standing; Digitised (various); 2-line Cobb T12-S1	Method-dependent
Jackson & McManus, 1994	USA; LBP≥6w (VAS) (n=100); Controls gender matched (n=100)	Standing Mod Cobb LL=L1-S1; TK=T1-T12	LL: LBP < Controls; LBP less distal segmental LL
Pope et al, 1995	#USA (M 18-55yrs) (n=321); LBP severe; LBP moderate; no pain	Standing Farfan; LL=L1-L5, L1-L3, L3-L5	ND
Hansson et al, 1984	Sweden/USA (M heavy labourers); LBP>6m (n=200); LBP first time (n=200); no pain age matched (n=200)	Pre-employment x-rays; Supine; goniometer on film; LL=L1-S1	ND
Frymoyer et al, 1984	#USA (M 18-55yrs) (n=321); LBP severe; LBP moderate; no pain	Standing Mod Cobb LL=L1-L5, L1-L3, L3-L5	ND
Brav et al, 1942	USA; LBP (n=62); Controls (younger, n=35)	NR	LL: LBP < Controls

LBP=low back pain; MRI=magnetic resonance imaging; LDH=lumbar disc herniation; NR=not recorded; Mod Cobb=modified Cobb technique; LL=lumbar lordosis; TK=thoracic kyphosis; ND=no difference reported; VAS=visual analogue scale; ht=height; wt=weight; #=same patient group employing different method; M=males

Cobb Method - constrained and non-constrained: The most widely used gold-standard technique for describing sagittal curvature is a modified method referencing vertebral end-plates that is based on the original description of Cobb (Cobb, 1948) for measuring scoliotic curvatures in the coronal plane (McAlister and Shackelford 1975).

Tangents through the vertebral endplates of each limit vertebra define the angle of the spinal region being investigated. The constrained Cobb technique, where the angle between two defined limit vertebrae is reported, is more commonly employed for the lumbar region, with fewer investigators using the non-constrained method that identifies the most tilted vertebra separating the thoracic and lumbar curvatures, as the upper limit. Studies using the constrained technique to measure LL have used various limit vertebrae. The terms lumbolumbar and lumbosacral lordosis typically refer to measuring between the upper endplate of L1 and the lower endplate of L5, and both the upper endplates of L1 and S1, respectively. Despite their prevalent application, no consensus on optimal limit vertebrae exists, which likely reflects a variable application that is dependent on individual studies and investigators. A summary of the methods employed by various studies is presented in Table 2.10.

Variability: Measurement of lumbar lordosis is marked by variability and intrinsic error, which has been attributed to various biological (patient and rater) and methodological sources (Robinson 1997). Biological influences include: subject posture (e.g. arm position, postural sway), muscle spasm, anatomical variability, rater experience, goniometric technique, precision in identifying and demarcating vertebral body surfaces, and even marking pencil thickness for hard-copy images (Polly et al. 1996). Literature discussing the physiological features of postural sway and morphometric differences is elaborated in the various parts of Appendices VII and VIII, respectively. Method-introduced errors may involve: image noise and effects of imaging like errors of parallax, subject positioning during image acquisition, and evaluation errors including inaccurate definition of end-vertebra and inconsistent identification of vertebral features (Vrtovec et al. 2009). Literature relating to methodology-based errors is outlined further in Appendices VII and IX.

The variability and visibility of end-plate anatomy can present landmark identification difficulties (Voutsinas and MacEwen 1986; Polly et al. 1996; Goh et al. 2000; Harrison et al. 2001), which may be further affected by radiographic distortion and magnification (Singer et al. 1990, 1994). Variability in end-plate architecture and end-vertebra selection has been shown to result in up to 10° variation between measures (Polly et al. 1996).

The Cobb method and its modifications are less effective in measuring lumbar curvature after a surgical procedure that involves disruption of the endplate, like interbody fusion, which is particularly true for the lowest two lumbar segments where surgical treatment is most commonly applied (Schuler et al. 2004). In the case of surgery with an ISP device, the endplates generally remain untouched perioperatively, thereby allowing for adequate landmark identification in applying the Cobb method for assessing skeletal alignment.

Table 2.10: Summary of investigations reporting radiography-derived skeletal curvature in asymptomatic populations indicating variable measurement methods, gender differences and age groups for lumbar lordosis (LL) and sacral inclination (SI).

Study	Method	Position	Limits	N	Gender	M/F	Age	LBP	LL	SI
Farfan et al, 1972	Σ upper & lower L/S	Cadaver	L1-S1	182	Unclear	No	20-100 (n=180>40)	N/A	Median 42 (10-67)	Sacral slope 26 (16-38)
Torgerson & Dotter, 1976	Cobb: C	Lateral	L3-S1	217	N/R	No	M 50-59	No	58 (43-80)	
							M 60-69		63 (45-95)	
							M 70-79		59 (40-80)	
							F 50-59		62 (45-95)	
							F 60-69		64 (48-80)	
							F 70-79		63 (40-90)	
Stagnara et al, 1982	Cobb: U	Stand	ITL-S1	100	M 57 F 43	No	20-29yrs	No	50 (30; 32-84)	41 (35; 19-65)
Fernand & Fox, 1985	Cobb: C	Lateral	L2-S1	949	M 322			N/R	42.9 (±0.6)	
					F 400				46.9 (±0.6)	
			L2-L5	973	M 330				27.4 (±0.6)	
					F 416				32.0 (±0.5)	
Propst-Proctor & Bleck, 1985	Cobb: C	Stand	L1-L5	104			2-20yrs		40 (22-54)	
Voutsinas & MacEwen, 1986	Cobb: U	Stand	ITL-S1	171	M 70	N/R	15-20yrs		57.4 (8.6)	58.2 (9.3)
					F 101				56.1 (9.4)	55.3 (9.2)
Bernhardt & Bridwell, 1989	Cobb: C	Stand	T12-L5	102	M 47 F 55	No	12.8 (5-30)	No	44.0 (12; 14-69)	
Jackson & McManus, 1994	Cobb: C	Stand	L1-S1	200	M a 50	No	38.9 (9.4; 20-63)	No	60.9 (±12; 31-88)	50.4 (±7.7; 28-68)
					F a 50		39.4 (9.0; 22-60)			
					M s 50	No		Yes	56.3 (±11.5; 24-84)	
					F s 50				[2]p<0.01	47.2 (±8.4; 18-67) [2]p<0.01
Cheng et al, 1998	Cobb: C	Stand	L1-L5	387	M 142	No	63 (8)	No	41.4 (12.3)	
					F 198		62 (8)		42.5 (11.7)	

Chernukha et al, 1998	Cobb TRALL	Supine	L1-S1	40	M4:F1	N/R	21-30yrs	N/R	52.6 (11.6) 47.2 (7.4)	
Korovessis et al, 1998	Cobb: C	Stand	L1-L5 T12-S1	99	M 38 F 61	No	52.7 (15; 20-79)	No	45.7 (±12; 11-95) 83 (±16; NR)	39.4 (11; 10-68)
Harrison et al, 2001	Cobb: C TRALL Centroid Post Tangent	Stand	T12-S1 L1-L5 L1-S1 T12-S1 T12-S1 L1-L5	30	N/R	-	-	-	58.6 (16.4) 40.3 (14.6) 41.2 (9.1) 56.6 (17.0) 66.1 (17.3) 34.5 (16.7)	
Korovessis et al, 2002	Cobb: C	Stand	T12-S1	200	M a100 M s100	N/A	49 (18) 46 (15)	No Yes	a: 52 (13) s: 49 (14) NS	33 (4) 37 (10) $^{1}p<0.05$
Vialle et al, 2005	Cobb: U	Stand	ITL-S1 L1-L5	300	M 190 F 110	Yes $^{3}p<0.001$	35 (20-70)	No	60.2 (10.3; 30-89) 43 (11.2; 13.6-69)	Sacral Slope 41.2 (8.4; 17-63)
Damasceno et al, 2006	Cobb: C	Stand	L1-S1 L1-L5	350	M 143 F 207 M 143 F 207	Yes $^{1}p<0.02$ Yes $^{2}p<0.01$	29.0 (8.2; 18-50)	No	59.3 (10.7; 33-88) 62.0 (10.5; 33-89) 43.0 (10.8; 15-78) 46.5 (10.6; 20-77)	
Mac-Thiong et al, 2007	Cobb: C Cobb: U	Stand	L1-S1 ITL-S1	30	M10 F20			Mix	C: 61.6 (13.9) U: 68.1 (16.7) $^{4}p<0.0001$	

Σ=sum; N/A=not assessed; N/R=not recorded; Cadaver=cadaveric x-ray; C=constrained; U=unconstrained; M/F=significant difference between genders; M=male; F=female; (x; x-x)=SD, range of values; (±xx)=standard deviation; a=asymptomatic; s=symptomatic; LBP=presence of LBP; yes=present, No=no LBP; $^{1}p<0.05$, $^{2}p<0.01$, $^{3}p<0.001$, $^{4}p<0.0001$=significant difference between cases with and without LBP

Polly et al (1996) recommended that for serial lumbar lordosis measurement there should be: comparison of consecutive films to confirm end-vertebra; consistent end vertebra selection across time-points; a specific technique used that is determined a priori; and a consistent method for end-plate line identification be executed.

A reported advantage of the non-constrained modified Cobb method is its allowance for length variability of the TK and LL within the thoracolumbar spinal curve (Mac-Thiong et al. 2007b). The relevance of this relates to the variable number of kyphotic and lordotic vertebrae that exist in the normal population (Vaz et al. 2002), and the variable thoracolumbar inflexion point (Vialle et al. 2005), which has been shown to move caudally, particularly in women, from the 7^{th} decade (Singer et al. 1990). The constrained and non-constrained methods are shown to highly correlate for the measurement of LL (Mac-Thiong et al. 2007b). The definition of end vertebra is reported to introduce the main source of error in using the Cobb method for angle derivation (Gstoettner et al. 2007).

The Cobb angle only reflects the orientation of the vertebral end-plates rather than the regional geometry of the curve itself, with the potential for two markedly different curves to be assessed as having the same angulation (White and Panjabi 1978; Stagnara 1982; Voutsinas and MacEwen 1986; Singer et al. 1990). Several alternative methods for assessing spinal curvature have been developed to overcome this limitation and provide improved utility in describing skeletal shape (Singer et al. 1990; Chernukha et al. 1998; Chen 1999; Harrison et al. 2001). The centroid (Chen 1999) and posterior tangent techniques (Harrison et al. 2001) have improved repeatability by reducing the impact of poor end-plate visibility; however are also criticised for their reference to end vertebra alone. Geometrical shapes like circles and ellipses are used to define sagittal spinal curvature in providing improved shape characteristics via complex mathematical modelling (Singer et al. 1990; Harrison et al. 2002; Pinel-Giroux et al. 2006). A computerised method deriving mean radius of curvature (RoC) based on anterior and posterior vertebral body contours in the thoracic spine (Singer et al. 1994), was shown to have superior utility compared to the Cobb angle (Goh et al. 2000). The identification of multiple landmarks along the entire curve using the RoC method renders it less susceptible to digitising errors compared to the Cobb method or its derivatives (Pinel-Giroux et al. 2006).

The segmental lordosis at L4-5 and L5-S1 constitutes more than half the regional lumbar lordosis (Stagnara 1982; Polly et al. 1996; Harrison et al. 2001) and those levels represent the most common for interbody fusion and interspinous implants (Deyo et al. 2004; Bono and Vaccaro 2007). A sagittal Cobb angle difference between LL and TK of more than 20º (LL higher) is considered optimal in maintaining sagittal alignment (Kim et al. 2006b).

2.10.3 Measuring sagittal balance:

Sagittal contour and balance are the principles that define the position of the head and trunk relative to the neutral axis, where cervical lordosis, thoracic kyphosis and lumbar lordosis are components. Assessment of sagittal spinal alignment is becoming more common (Labelle et al. 2004; Berthonnaud et al. 2005; Roussouly et al. 2005; Mac-Thiong et al. 2007a; Lafage et al. 2008) as surgical outcomes, particularly in scoliosis, are increasingly recognised as dependent on the sagittal plane (Smith et al. 2002; Mac-Thiong et al. 2008). Global sagittal balance (GSB) of the spine is quantified by measuring the position of the C7 vertebra with respect to the posterior superior corner of S1. This measurement is termed the sagittal vertical axis (SVA) and describes the cumulative balance of the sagittal spinal curves (Roussouly et al. 2006). The SVA, or plumbline, is determined via a standing lateral full-length spine radiograph (O'Shaughnessy and Ondra 2007). The radiographic procedure requires the subject to habitually stand in bilateral knee extension, with the feet positioned shoulder-width apart (Stagnara 1982). The subject's arms are generally in a position of elevation to enable optimum visibility of key vertebral landmarks. Adopting the 'clavicle' position has been shown not to bias the measurement of sagittal balance, while being relaxed and comfortable for the subject (Horton et al. 2005). Sagittal balance, measured in millimeters, is typically determined from the SVA as it falls from the centroid of the most cephalad visible vertebra, referenced to a standardised sacral landmark which is typically the posterior-superior corner of the first sacral vertebra (S1) (Jackson and McManus 1994; O'Shaughnessy and Ondra 2007; Lafage et al. 2008).

Descriptions of sagittal balance vary. It is commonly held that the terms global sagittal balance (GSB), or C7-plumbline, refer to displacement of the thoracolumbar spine from a C7-centred SVA. Reference to regional sagittal balance should identify the upper-most vertebra from which the plumbline falls. Jackson and McManus (1994) found that a vertical plumbline from the centre of the C7 vertebral body transected the L1 vertebra in patients with low back pain, and the L1-2 intervertebral disc in healthy volunteers. The L1 axis S1 distance (LASD) has been reported as a method for assessing lumbar sagittal alignment (Kawakami et al. 2002). The LASD equates to lumbar sagittal balance as determined via a regional (lumbar) radiograph, and represents the horizontal distance between the plumbline from the first lumbar vertebral centroid, and the posterior-superior corner of the first sacral vertebra (S1). Both the vertical L1 plumbline, and the horizontal line between the measured points, are referenced to the edge of the radiographic film where verticality is assumed (Kawakami et al. 2002).

Normal GSB in adults, as derived from radiographic plumbline, is said to fall within a narrow range from the sacral reference point (O'Shaughnessy and Ondra 2007). Positive and negative sagittal balances have been defined as an anterior or posterior deviation of the GSB measurement from the sacral reference, respectively (Glassman et al. 2005b; Kuklo 2007; O'Shaughnessy and Ondra 2007). Asymptomatic adults have been shown to have a mean GSB of 5 mm (SD 25 mm) (Jackson and McManus 1994) suggesting abnormality in individuals with values in excess of 25 mm either posteriorly or anteriorly. It is commonly held that an increasing GSB occurs with age and sagittal plane pathology (O'Shaughnessy and Ondra 2007). Positive values are more associated to pain and disability than curve magnitude or location, or coronal imbalance (Glassman et al. 2005a).

Accuracy of the sagittal balance measurement based on an erect lateral radiographically-derived SVA is questioned in a study investigating variability due to postural differences in an individual with fixed spinal deformity (Van Royen et al. 1998). The authors revealed variation in sagittal balance due to small changes in hip, knee and ankle joint positions, concluding that caution should be applied if employing the measurement in spinal deformity research and practise. Interestingly, the same authors took care to control for the position and fixation of the long-cassette film by using a radio-opaque plumbline in their radiographic image. Lafage et al (2008) have highlighted the compensatory role that the pelvis plays in equalising sagittal balance. They revealed that an increasing GSB lead to a posterior pelvic shift in relation to the feet, with no difference occurring in the offset between the gravity line and the heels. This finding was reported to confirm the earlier work of Schwab et al (2006), which provided quantitative support for the “cone of economy” concept they credit to Dubousset. This concept underpins the notion that a standing individual maintains their centre of mass utilising a narrow sway range in relation to the feet. The impact of postural sway on thoracolumbar curvature is explored further in Appendix VI.

2.10.4 Defining point-placement*:*

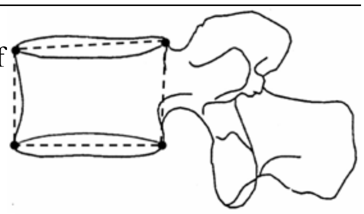
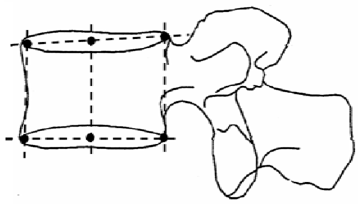
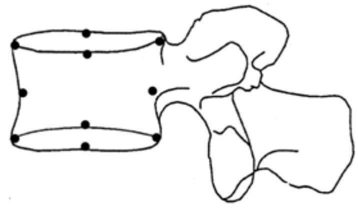
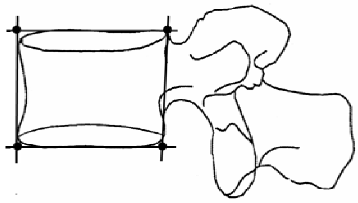
Various point-placement methods have been described in defining vertebral body dimensions in assessing plain radiographic films, manually or via digital means. Table 2.11 summarises four common methods that were considered for application in this thesis investigation. The number of points between studies used to define the vertebral bodies varies from four to ten, with the different point placements partly representing the variability of study aims between investigations.

2.10.5 Patient positioning:

All radiographic measurements depend on visual identification of key vertebral landmarks, and therefore clarity of imaging is of utmost significance. Anterior-posterior and lateral radiography for spinal alignment and deformity should be taken with the subject looking straight ahead in an upright position, with the knees extended, and feet positioned shoulder-width apart (Kuklo

2007). Horton et al (2005) revealed the 'clavicle position' produced best overall visualisation of the thoracolumbar spine, and had a neutral affect on global sagittal balance (GSB) by not unnaturally leaning the patient backwards. This position requires a patient's fists to be lightly clenched and resting on ipsilateral clavicles, resulting in bilateral shoulder angles of around 30 to 45 degrees. Although Horton et al (2005) found regional measures of lordosis and kyphosis were unaffected by patient position, they promoted the relaxed, clavicle position to be consistent for standardised measurement of segmental lumbar lordosis (Horton et al. 2005).

Table 2.11: Summary of four methods used to define vertebral body dimensions from plain radiographic images in assessing skeletal curvature.

Author(s)	**Year**	**Method Description**	**Illustration**
Farfan	1973	4-points (anterior and posterior VB corners), lines made in the direction of the end-plate, bridged concavity, transected convexity	
Spencer et al	1990	6-points (anterior, midline, posterior VB), spurs excluded, innermost anterior edge, midline posterior edge, midline ellipses for bases	
Melton et al	1993	10-points (3 anterior & posterior, 4 each base), inside corners of intersect between rims and edges, midline anterior and posterior, midline base ellipses	
Harvey & Hukins	1998	4-points (VB corners; may sit outside actual), intersected lines inclusive of projections	

VB=vertebral body. Images adapted from the four associated studies (Farfan 1973; Spencer et al. 1990; Melton et al. 1993; Harvey and Hukins 1998).

2.10.6 Summary:

Radiography, as employed in measuring serial skeletal spinal curvature, has been reviewed in relation to its use in the present study in assessing cases undergoing DIAM-augmented lumbar surgery. The assessment of lumbar alignment including lumbar lordosis and sagittal balance is described, with reference to techniques used for point-placement on digital radiographs, and optimal patient positioning.

CHAPTER 3

Methods

3.1 Overview

The main aim of this study was to investigate clinical outcomes in patients who received lumbar surgery augmented with the DIAM interspinous implant in treatment of their lumbar spinal disease. Several methodologies were employed to test the study hypotheses. These included: patient self-reported HRQoL to primarily assess back-specific function, low back, and back-referred leg pain; video rasterstereography for the assessment of surface lumbar posture; and conventional 'gold standard' skeletal lumbar assessments by spinal radiography. Additional aspects of the studies included a cohort of healthy volunteers to examine the normal variability of standing posture over 24 months.

The research design, study hypotheses and project aims are outlined in the beginning of this chapter (3.2 and 3.3). Section 3.4 details aspects of subject recruitment, including the inclusion and exclusion criteria, plus ethical considerations for this study. Section 3.5 outlines the sequence and implementation of the various tests. The questionnaire used in this study to assess the subjects' HRQoL including their back-specific function, low back and leg referred pain, general health, medication use, activity levels and self satisfaction, is described in Section 3.6.2. The assessment of thoracolumbar surface curvature using the video rasterstereographic system to assess healthy volunteers, a thermoplastic back phantom and the surgical cases, is described in Section 3.6.3. Section 3.6.4 explains the protocol used for spinal radiography, the criteria used to define vertebral landmarks, the determination of regional and segmental lumbar skeletal curvature including lumbar lordosis via the constrained Cobb method, disc angles employing tangential lines, lumbar regional sagittal balance, and regional shape characteristics as determined through calculating the radius of curvature. The statistical approaches adopted in testing the study hypotheses are presented separately according to each section. Where relevant, cross references to Appendices are made, to elaborate details.

3.2 Research Design

3.2.1 Phase I - Retrospective arm

This early hypothesis-generating arm of the study involved a retrospective audit of patient self reported HRQoL data that had been collected prospectively by the collaborating neurosurgeon prior to the genesis of the present investigation (Crawford et al. 2009a). No previous group analysis of the data had been performed. Phase I represents an observational cohort design based on the descriptions outlined by Hanson & Kopjar (2005) in describing clinical studies in spinal surgery.

3.2.2 Phase II - Prospective arm

The main arm of the investigation involved a prospective longitudinal observational cohort study, which followed patients from a single neurosurgical practice after they had received lumbar surgery augmented with the DIAM interspinous implant implanted by the same neurosurgeon. Methods for this arm of the study were in part informed by the first phase.

As an adjunct to the two year study of surgical cases, a small group of healthy volunteers were assessed for change in surface thoracolumbar curvature over the same time course to act as normative controls for the surgical group.

3.3 Research Hypotheses

This project reviews the clinical outcomes of individuals who underwent surgical intervention augmented with DIAM interspinous implant in treatment of their low back (and leg) pain. The first phase involved a retrospective review of 2 year clinical outcomes data of patients from one private Perth neurosurgical practice. Phase 1 was employed as a hypothesis-generator to inform aspects of the main investigation. The second and main phase of the study involved a prospective review of clinical outcomes following lumbar DIAM interspinous implant surgery plus an assessment of the implants' putative effects on lumbar morphology and posture.

3.3.1 Phase I: Retrospective review of clinical outcomes after lumbar DIAM-augmented surgery

This arm of the investigation analysed DIAM-augmented surgical patients according to diagnostic group, aiming to identify those who best responded to DIAM interventions for: predominant discogenic or zygapophysial joint spine disease. The clinical reasons for surgery, including: facet loading, segmental instability secondary to degenerative spondylolisthesis, central canal stenosis and nerve root compression secondary to foraminal stenosis were examined to predict postoperative responses. The proportion of single versus multi-level DIAMs implanted, and the distribution of implants per spine segment, were assessed along with their related pathologies.

Phase I Hypotheses: The primary hypotheses for this retrospective phase were that:

1. Lumbar surgery augmented with DIAM results in improved back and leg pain, function, general well being and satisfaction compared with preoperative baseline using accepted

definitions for MID.

2. Patients who undergo the addition of a DIAM interspinous implant in treatment of predominantly zygapophysial joint dysfunction will have improved outcomes over those with discogenic pathologies based on accepted definitions for MID.

3.3.2 Phase II: Prospective review of clinical outcomes after lumbar DIAM-augmented surgery

This main study arm aimed to prospectively investigate clinical outcomes for a patient cohort receiving lumbar surgery augmented with DIAM, in order to predict responders. The primary study aim was to recommend a clinical pathway algorithm to guide decisions regarding the use of DIAM in the lumbar spine. The efficacy of DIAM interspinous implant was examined according to both anatomical and diagnostic patient categorisation.

Components of the study separately investigated:

1. The role of DIAM interspinous stabilisation device on patient self-reported clinical outcomes, particularly emphasising back and leg pain and function.

2. Associations between clinical outcomes as assessed by a self-report health questionnaire at baseline, 6 weeks, 3, 6, 12, 18 and 24 months postoperatively.

3. The effect of the DIAM interspinous stabilisation device on mechanics and morphology of the lumbar motion segment including: disc angle, segmental vertebral position and lumbar curvature and alignment. Standing lateral radiography and back shape analysis through rasterstereography were employed to assess curvature and morphology.

Phase II Hypotheses (Surgical): The primary hypotheses for the prospective phase pertaining to the surgical cases were that:

1. Patients who undergo lumbar surgery augmented with a DIAM interspinous stabilisation device will have a significant time-dependent improvement in pain, function, general well-being, disability and satisfaction compared to their preoperative baseline level based on accepted definitions for MID.

2. Patients with primary zygapophysial joint anatomical involvement will show improvement whether they received DIAM for: spinal stenosis (foraminal or central canal); facet unloading; or degenerative spondylolisthesis, and will have superior outcomes than for those with disc or combined disc-facet segment disease based on accepted definitions for MID.

3. No change to surface thoracolumbar curvature, as determined via rasterstereography,

will occur after surgery augmented with DIAM interspinous implant over a two year time course.

4. A skeletal relative segmental kyphosis will be detected at the primary level of DIAM implantation early into the post-operative period through radiographic analysis.

5. Skeletal regional lumbar curvature will not change after surgery augmented with DIAM interspinous implant at any stage over one year compared to baseline.

Phase II Hypotheses (Healthy): The primary hypotheses for the prospective phase pertaining to healthy volunteers were that:

6. No change to surface thoracolumbar curvature, as determined via rasterstereography, will occur in healthy volunteers over a two year time course.

7. Variability in thoracolumbar sagittal balance, as determined via rasterstereography, in healthy volunteers of a wide age range would exist within and between individuals.

In addition to these primary hypotheses, related methodological hypotheses were:

In relation to Hypothesis 3:

3.1 Rasterstereography is a repeatable and reliable measure of lumbar lordosis for healthy volunteers and symptomatic back pain populations.

In relation to Hypothesis 4:

4.1 Measurements of segmental spinal curvature based on digital plain radiographic images will be sensitive to change in skeletal lumbar regional alignment and segmental disc angle, particularly at the primary level implanted with a DIAM.

3.4 Subject Recruitment

3.4.1. Phase I Retrospective arm

Patient selection and associated inclusion and exclusion criteria were applied retrospectively to an initial cohort of 101 consecutive operative cases who had received lumbar surgery augmented with DIAM in treatment of their lumbar spine disease. All patients received their surgery at a single private neurosurgical practice in Perth, Western Australia between February 2005 and July 2006. Enrolment criteria required demographic, surgical and clinical outcomes data from the preoperative baseline through to two years postoperatively. Baseline, 12 and 24 month post-operative data were considered essential for inclusion. Prior to auditing data, all patients were given a subject information sheet and informed, signed consent was sought (Appendix I.1). This arm of the study was approved by the Human Research Ethics Committee, The University of Western Australia [RA/4/1/1743] (Appendix II.1).

During analysis of this formative investigative arm, the author acknowledged the highly selected nature of the case series that constituted the subjects for Phase I [reported in the paper presented in Chapter 4 (Crawford et al. 2009a)]. As outlined above, patients were selected from the records of a single surgeon and had accessible two year responses. The final subject numbers represented a modest proportion (n=39) of the total cases that received the intervention during the time-period in question (n=101). Rejection of a potential subject usually arose from a lack of baseline data. This was particularly prevalent for the surgeon's earliest surgical cases when, at the time, a later study was not planned. In order to avoid a similar selection bias (Hanson and Kopjar 2005) in Phase II of the study a patient selection strategy was planned a priori, and discussed below.

3.4.2 Phase II – Prospective arm

Surgical: The surgical subjects for the prospective arm of the investigation were also patients from the same single neurosurgical practice in Perth. Consecutive patients between 1st June 2007 and 31st May 2008, who were seen by the surgeon and were subsequently triaged for DIAM-augmented surgery, were enlisted for potential inclusion in the study. Inclusion criteria were then applied to this set of patients. On the same day that the neurosurgeon made the clinical decision to treat an individual with lumbar surgery augmented with a DIAM, each patient was provided with an information sheet outlining the 24-month serial study. The surgeon requested signed informed consent from each patient for his or her inclusion during this initial consultation. These two documents can be found in Appendices I.1 and I.2. Consenting patients were then required to complete their first (baseline) self-reported questionnaire during this decisive preoperative surgical consultation. Additionally, subjects were categorised by the surgeon preoperatively based on a set of predetermined options that were compiled by the author as a synthesis of the clinical literature reporting indications for the use of the device. Before study commencement, confirmation that the categories reflected the surgeon's own clinical reasoning and perceived indications was sought to ensure their relevance to his practice (Malone 2007a). The check-list and categorisation forms employed at the neurosurgical practice are included in Appendix III, the details of which are explained later in 3.7.2. Demographic information, relevant preoperative imaging findings, previous history of interventions, perioperative details and corroboration of each individual's inclusion in the study, were obtained by the author from each patient's case notes within four weeks of having received their surgery. Each recruited patient was assessed via the HRQoL instrument at baseline as the basic minimum preoperative outcomes data. Their inclusion for surface and skeletal curvature assessment was dependent on other factors, which are outlined later.

Where time and geographical locations allowed, subjects were referred for preoperative radiographic and rasterstereographic assessment prior to their hospital admission for surgery. The radiographic investigation was also part of the routine preoperative surgical workup. Individuals who were unable to attend for either of these two preoperative imaging investigations were retained to follow-up in order to assess their self-reported clinical outcomes only. Self-reported patient outcomes were serially assessed at the 6 week, plus 3, 6, 12, 18 and 24 month post-operative time-points to coincide with their surgical review. If no review was required, they were posted a questionnaire with a stamped, self addressed envelope for ease of return on completion. In the event a questionnaire was not returned, the patient was telephoned and reminded to do so by the surgery practice staff after prompting from the author.

Those individuals whose surface curvature was assessed at baseline were subsequently re-assessed at the 6 week, 6, 12, 18 and 24 month post-operative time-points. Baseline assessment plus later contact and appointments with the rasterstereography cases were all conducted by the author. The surgeon referred all cases for radiographic imaging at pre-operative baseline, 6 weeks and 12 months postoperatively. This was done as a routine aspect of management, assessing their post-operative skeletal alignment. From approximately the 10th enrolled case, each individual's digital radiographic images were electronically available to the author directly from the surgeon's rooms. In the event that no image was received for a time-point by an expected date, the patient was contacted by the surgeon's office staff and reminded to action their referral.

Healthy: Healthy volunteers for the study were sought via word of mouth. Participation was purely voluntary with no remuneration offered.

3.4.2.1 Inclusion Criteria:

Surgical: For the surgical subjects to be included in this study, they had to be appointed to receive lumbar surgery augmented with a DIAM from the same neurosurgical practice, performed by the same surgeon, and have provided written informed consent for study inclusion. All cases scheduled for surgery with a single or multiple DIAM(s) in treatment of their lumbar degenerative disorder from 1st June 2007 through to 31st May 2008 were registered, based on the exclusion criteria outlined below. Cases with at least one postoperative time-point data were retained.

Healthy: Healthy volunteers were included in the widely aged convenience sample if they had no current symptoms (two weeks prior to the baseline measures) of low back or leg pains, and could stand comfortably without symptoms or poor balance requiring assistance.

3.4.2.2 Exclusion Criteria:

Surgical: Participants who were unable to reliably self-report their pain or functional status without an interpreter due to a poor command of English, as determined by the collaborating neurosurgeon, were immediately excluded (n=5). Those patients who did not confer their consent after reading the information sheet were not progressed to the study group (n=8). Patients with coexisting carcinoma were excluded (n=2). Patients who were intended for DIAM implantation in order to 'top-off' an interbody fusion were not included (n=2). Patients who had previous lumbar surgery augmented with a DIAM were excluded (n=7), as were those who had a past history of other more destructive lumbar surgeries like lumbar interbody fusion (n=4) or extensive decompression (n=9). Four cases were also not progressed to inclusion by the neurosurgeon, without explanation in their respective case-notes. Individuals who had received previous minimally invasive lumbar decompression via microdiscectomy without an ISP device were included if the DIAM-augmented surgery was intended for an alternative segmental level, or for a reherniation or degenerative disc disease at the original surgical site. One case was scheduled for surgery, which was later cancelled due to other unrelated serious pathology and was therefore removed from the database. One recruited subject was intended for decompression augmented with a DIAM, however a perioperative decision not to implant the device was made by the surgeon. This individual was excluded from further follow-up. One patient died as a result of a motor vehicle accident shortly after their surgery and prior to their 6-week follow-up. Baseline results initially obtained for this individual were excluded. One patient failed to complete any postoperative time-point surveys despite every effort to retain the individual, and was therefore not able to be included for serial follow-up. As a result of the inclusion/exclusion conditions, 45 potential patients from the consecutive year-long list (n=126) were not included, leaving the Phase II cohort comprising 81 cases. The patient selection of the prospective cohort has been schematically presented in Figure 3.1.

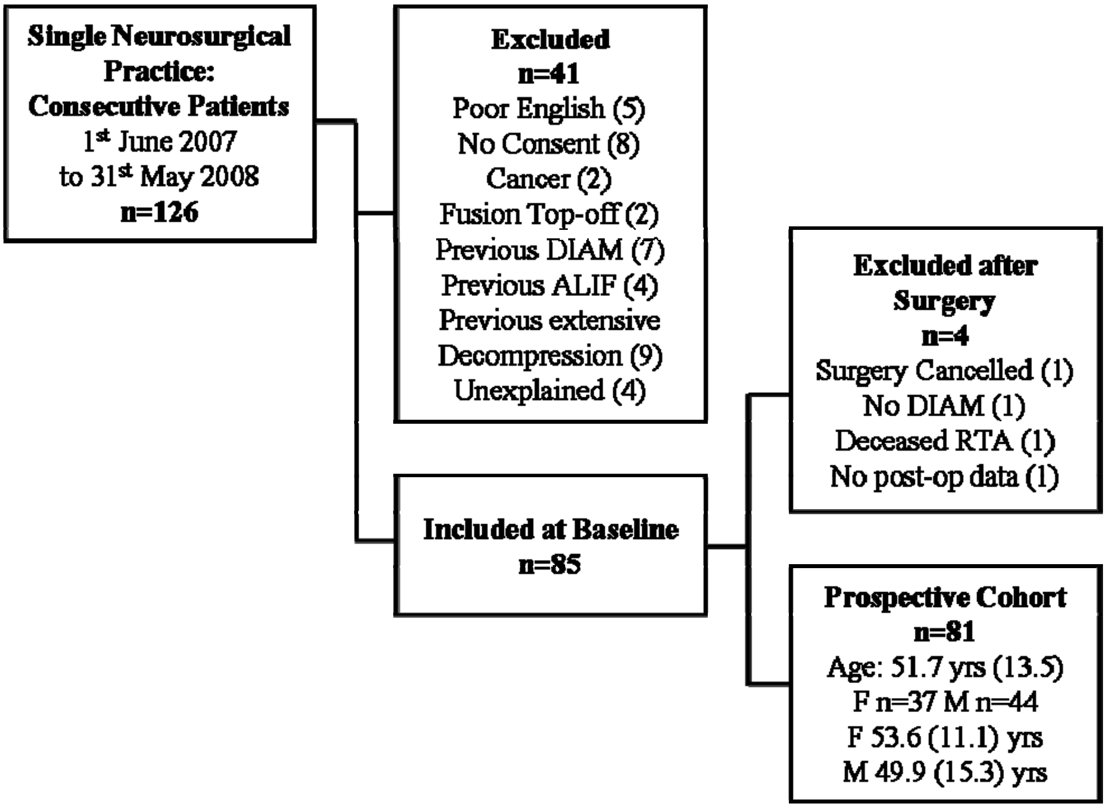


Figure 3.1: Organisation chart presenting the patient selection process in relation to the relevant exclusion criteria

3.4.2.3 Ethical Considerations: The prospective arm of the study was approved by the Human Research Ethics Committee, The University of Western Australia [RA/4/1/1766] (Appendix II.2).

3.5 Sequence of tests: Prospective Phase

Patient outcome assessments for this study were conducted over various time-points and in several locations. The HRQoL questionnaire was either completed in the surgeon's rooms to coincide with a surgical review consultation, in the rasterstereographic testing room of the author, to coincide with a surface curvature assessment appointment, or at the patients chosen location had they been sent the survey by post. Surface curvature assessment was completed in a dedicated research room at the Centre for Musculoskeletal Studies, located in the Medical Research Foundation Building, Royal Perth Hospital, Perth. Radiographic assessments were completed at any of the 14 metropolitan radiology practices of the private business, Perth Radiological Clinics. The patient chose the location according to their convenience.

3.6 Clinical outcome measure: Retrospective Phase

The retrospective arm audited self-reported clinical outcomes that were prospectively collected from 39 cases (21 females, 18 males) that received lumbar surgery augmented with the DIAM interspinous implant at a single Perth neurosurgical practice. Patient data were derived from completed MODEMS questionnaires received from patients at various time-points in their operative course. Specific details of the questions used to describe change in these patients over the two year period are described in greater detail in Chapter 4, which presents the published results of the retrospective phase (Crawford et al. 2009a).

3.7 Clinical outcome measures: Prospective Phase

This thesis, and in particular the prospective phase, aimed to contribute to the provision of clinical guidelines for lumbar surgery augmented with the DIAM interspinous implant. Serial patient-reported HRQoL was assessed, in addition to spinal curvature as determined both from the skin surface via rasterstereography, and skeletally via plain lateral standing radiography. An a priori intention was to apply multiple subset analyses within and between these outcome assessments, in the foreknowledge of the limitations of multiple statistical comparisons, in order to identify prognostic determinants of response over two years. Variables employed to achieve this are explained below.

3.7.1 Patient demographic information

The prospective arm cohort included 81 cases [37 females, 44 males] from an initial consecutive series of 126 patients (Figure 3.1) sourced from a single-surgeon private neurosurgical practice.

Age: The mean age (SD; range) of the group was 51.7 years (13.5; 20-80). Females averaged 53.6 years of age (11.1; 24-80), while male subjects were 49.9 years (15.3; 20-79) old. Eleven females and 21 males were under 50 years, and 26 females and 23 males were over 50 years old.

Classification via the surgeon: The surgeon was tasked with classifying the patients preoperatively at the time of their decisive baseline consultation, and in accord with his preoperative intentions for their surgical management. He was asked to categorise each patient based on their: anatomical pathological predominance as originating from the disc, facet or in equal contribution from both (mixed); and clinical diagnosis warranting surgery as lumbar spinal stenosis [LSS; foraminal [and/or lateral recess] (FS) or central canal (CS)], facet joint pain syndrome (FJPS), or degenerative spondylolisthesis (DS). Diagnosis was based on the surgeon’s own clinical impression of the patient’s clinical history and associated imaging studies that were confirmed with facet joint injections, diagnostic blocks, and discography, according to his routine practise. In order to capture the surgeon's clinical reason for implanting the DIAM, patient symptoms were linked to the four diagnoses. Therefore, on the diagnosis categorisation form presented in Appendix III.2, FS appears as "nerve root compression", CS as "canal stenosis", FJPS as "facet unloading", and DS as "instability". The surgeon indicated the patient's primary lumbar segmental level for which the surgery was deemed necessary and each other (secondary) level in the case of those where multiple DIAMs were intended. These were summed to indicate the number of DIAMs determined for each case preoperatively. The surgeon was asked to record a list of relevant comorbidities for each patient.

The author verified each stage of this categorisation process with a careful audit of the patient's case notes including any available preoperative imaging and communications, the peri-operative surgical report (completed by the surgeon immediately after surgery), and any written post-operative communications between the surgeon, patient, and other associated medical practitioners that were kept on file by the surgeon. This post-operative audit also compiled data concerning the size of the DIAM implanted at surgery [8, 10, 12, or 14mm device] and whether their DIAM implantation augmented a single, or multiple decompression technique(s). Decompression technique terms used by the surgeon included: decompression, microdiscectomy, laminotomy, and foraminotomy. Two cases (one per gender) had no decompression technique recorded, which was confirmed by the surgeon to indicate insertion of the device in isolation (Malone, 2008). Unless otherwise stated in the patient case notes, it was assumed that surgery involved: standardised microscopy-enabled procedure, with the patient positioned prone on a Wilson table, a midline incision, unilateral reflection of the paraspinal muscles, subperiosteal approach to the interlaminar space, the indicated decompression technique(s), insertion of the DIAM whose tethers had been removed, and with retention of the supraspinous ligament (Figures 2.8 and 2.9).

Case numbers per gender and according to the pre-operative patient categorisation are presented later in Table 7.1.

Postoperative protocol for all patients undergoing DIAM-augmented lumbar surgery via this surgeon is a 6 week postoperative rehabilitation programme (or longer as indicated) that is managed by a single private physiotherapy practice. The primary goal of the individually tailored McKenzie-based exercise programme (McKenzie and May 2003; Lynn 2009) is restoration and optimisation of functional upright postures (Lynn 2008). Patients commence this programme within the first 24 hours postoperatively, and are then seen at discharge from inpatient care, and reviewed at four and six weeks postoperatively, the latter to coincide with their review consultation with the surgeon. All in-patient care was provided by one physiotherapist and outpatient care with one of two long-term collaborating physiotherapists of equivalent training and experience (Lynn 2009). Cases who received adjunctive microdiscectomy were initially instructed to avoid flexion activities to encourage healing of the posterior anulus. The early aim for all other cases was to restore lumbar lordosis (Lynn 2008).

3.7.2 Patient self reported HRQoL questionnaire

The prospective phase utilised a single questionnaire developed by the author and based on recommendations outlined for back pain research, as defined in the literature and presented earlier (Chapter 2). In attempts to optimise patient-compliance, a short, concise battery of questions was compiled (Edwards et al. 2002). The questionnaire included: ten Oswestry Disability Index (ODI) (Version 2.0) questions as a measure of back-specific function; one VAS measuring back pain; one VAS measuring leg pain; one question revealing each patient's satisfaction with their current status; one question describing medication use; two questions revealing the effect of their present symptoms on work and activities of daily living; and a section allowing for patient comments. The questionnaire asked subjects to respond based on their symptoms on the day (of questionnaire completion). If any explanation of responses was required, the author telephoned or contacted the patient personally (as the situation allowed) to seek clarification. This was only necessary on five occasions. The HRQoL questionnaire employed in this study is included for reference in Appendix V. The ODI responses were summed and presented as a percentage. Any missed responses, particularly those relating to the 'sex' question, were accommodated [according to protocols for using the instrument (Fairbank and Pynsent 2000)] within the percentage computation. Back and leg pain according to VAS were also recorded as a percentage. Satisfaction and medication use were noted as a number based on a 5-level Likert scale (1=very satisfied/not at all; 2=somewhat satisfied/once a week; 3=neither satisfied nor dissatisfied/once every couple of days; 4=somewhat dissatisfied/once or twice a day; 5=very dissatisfied/three or more times a day). Two activity questions were employed as a measure of work-related disability and were recorded according to number of days.

Patient's self reported HRQoL was measured using the questionnaire at seven time-points in their pre and post-surgical course. Time-points included: preoperative baseline, plus 6 weeks, 3, 6, 12, 18 and 24 months postoperatively. Questionnaires were variously distributed to patients as indicated earlier in Section 3.5. Data derived from patient responses were entered into a spreadsheet (Microsoft Office Excel 2003; Microsoft®; Redmond, WN, USA) that was further organised using Excel's pivot table and descriptive statistics functionality.

Statistical Analysis:

Missing data: In the case of missing HRQoL data where a patient: omitted a response on the questionnaire; failed to provide data at mid-course time-points but otherwise had complete end-point data; failed to provide data as a result of being lost to follow-up or an inability to complete later time-point measures relating to geographical relocation to an unknown address, illness or apathy; or were excluded from follow-up as a result of requiring additional lumbar surgery, either as a revision of DIAM implantation or progression to disc replacement, laminectomy or interbody fusion, then the last-value-carried-forward (LVCF) single longitudinal imputation method was employed (Twisk and deVente 2002; Shao and Zhong 2003). This method has been reviewed earlier in Chapter 2.3 and was employed to mitigate patient selection bias on a quasi-intent-to-treat basis (Landewe and van der Heijde 2007). All 81 patients provided complete baseline and six week postoperative data; 20 cases had an episode of missing data over the 24-month period. Appendix XII provides details of the raw data available for each case.

Data treatment: Patient self-reported HRQoL were analysed in an exploratory manner based on the observational nature of the investigation. Sub-set analyses were used to identify prognostic determinants of responders based on pre and postoperative features. Data were analysed using Microsoft Excel 2003 and StatView (Abacus Concepts, Inc., Berkley, CA, USA, 1992).

Descriptive statistics were derived for demographic, baseline and serial time-points for each of the HRQoL variables. Change scores compared to preoperative baseline were employed in two ways: time-point value minus the baseline value (e.g. 6 weeks minus baseline); and time-point value minus the baseline value, divided by the baseline value. Change scores calculated on the absolute difference between patient-reported values at two time-points were referred to as absolute change [e.g. 12 month value minus baseline value; 12m-B], while change normalised to the baseline value is referred to as normalised change [e.g. absolute change divided by baseline value; (12m-B)/B]. Change scores between two time-points were analysed according to subject sub-sets using unpaired t-tests with the change score as the continuous variable, and subject categories as the nominal variable. Line charts depicting individual's pain (VAS back and leg) and function (ODI) over the two year period were displayed. Box-plots were used to summarise the serial data for all cases with baseline, plus 6 weeks, 3, 6, 12, 18 and 24 month postoperative data for each variable. The standard format for all box-plots uses horizontal lines, which from the top represent the 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles, respectively.

Repeated analysis of variance [ANOVA (with Scheffe's post-hoc test)] was used to analyse serial changes. Serial group results for each variable were split according to their gender, age group (≤50yrs<), anatomical, and diagnostic preoperative categorisations, DIAM primary implant level, and number of DIAMs implanted. Selected aspects of these analyses are also presented using box-plots. Associations between variables at baseline and change between time-points were indicated with Pearson's correlation coefficients. Statistical significance was defined as $p<0.05$ to represent a meaningful difference.

MID and Responder Analyses: Responders were identified according to their self-reported improvement in back and/or leg pain and back-specific function as measured with the VAS and ODI outcome tools, respectively. Degree of improvement considered acceptable in defining a responder based on MID recommendations for each outcome measure was explained in Chapter 2. When absolute change scores were analysed, improvement was deemed of moderate clinical importance for function, back and leg pains when 30% or greater reduction in ODI (function) or VAS (back and leg pain) scores occurred. Reductions over 15% for ODI (function) and 20% for VAS (pain) scores represented a minimum acceptable change. Changes less than minimally acceptable were categorised as non-responders. When relative change scores were analysed, improvements in function, back and leg pains that were equal to, or in excess of 20% for VAS or ODI were considered minimally acceptable, while 30% or more improvement was recorded to be of important clinical significance. The values for relative change were based on the lower and upper values described for MID by Ostelo et al (2008). Subjects reporting change in actual or relative pain or function in excess of 50% were considered to have shown substantial improvement.

3.7.3 Rasterstereographic methods for assessing surface curvature

Back shape imaging was performed utilising the Jenoptik Formetric video rasterstereography system (Aesculap Meditec GmbH, Germany), which has been described in Chapter 2.3.

Subjects and serial assessments: Surface spinal curvature for: eleven healthy volunteers; a thermoplastic back phantom [based on a 14 year old female previously reported as having a mild scoliosis (Goh et al. 1999b)]; and 39 cases from the prospective surgical cohort, were assessed over a two year period. Healthy volunteers had to have been back pain-free for two weeks prior to any assessment. Five successive rasterstereography images were taken per session and completed on five occasions: at baseline/preoperatively, 6 weeks, 6, 12 and 24 months later or postoperatively for the healthy and surgical subjects, respectively; and on two occasions two years apart for the thermoplastic back phantom. An interim time-point at 18 months postoperatively was included for surgical cases (where possible) and was used as an alternative to the 2-year time-point for those unavailable for that follow-up.

Measurement of the back phantom was used to assess system accuracy. Subject demographics of the healthy volunteers and the methods employed in assessing their surface curvature over the two year period, are elaborated in Chapter 5. Chapter 6 presents a paper reporting the results for surface lumbar lordosis in a subset of 10 healthy volunteers versus 10 surgery patients in the early postoperative stage (Crawford et al. 2009b). The methods employed for deriving surface curvature via rasterstereography for this study were the same across all surgical cases; however the methods description to follow reports for the entire cohort assessed.

Surgical cases: The decision to refer patients for rasterstereographic assessment was governed by the neurosurgeon. Surgical cases were referred for surface curvature based on the surgeon's determination of their: consent at consultation, availability within 4 weeks of surgery to attend for assessment, and perceived tolerance to the rasterstereographic assessment. Patient tolerance related to their ability to stand erect for 5 minutes and travel to the dedicated testing office (less than a 15 minute drive or a convenient free bus ride from the surgeon's consulting rooms). Surgical subjects were given the rasterstereography referral form (Appendix IV.1) and asked to telephone the author to arrange an appointment, which was then made at the patient's convenience. Age and gender demographics for the surgical cases assessed for their surface curvature are outlined in Figure 3.2, according to the numbers assessed at each time-point.

Subject positioning: Imaging and analyses were achieved according to a modified protocol that was loosely based on Goh et al's (1999) description in assessing osteoporosis. The author undertook all rasterstereographic assessments in a room dedicated for the purpose within a medical research facility of the university (Chapter 3.5). Healthy and surgical subjects were assessed in their underpants (women were requested to remove their bra) in a darkened room, without footwear, and standing on a stable surface of soft-pile carpet. Necklaces were removed and head hair that obscured the shoulders or vertebral prominens was secured out of the way.

Healthy subjects were asked to adopt their typical relaxed standing posture with their arms by their side. In the case of the thermoplastic back phantom; this was manually placed upright on a chair for support. Surgical subjects were instructed to stand in the clavicle position in order to best approximate the posture used for skeletal radiographic assessment (Horton et al, 2005). No external supports during standing were used for the healthy or surgical cases.

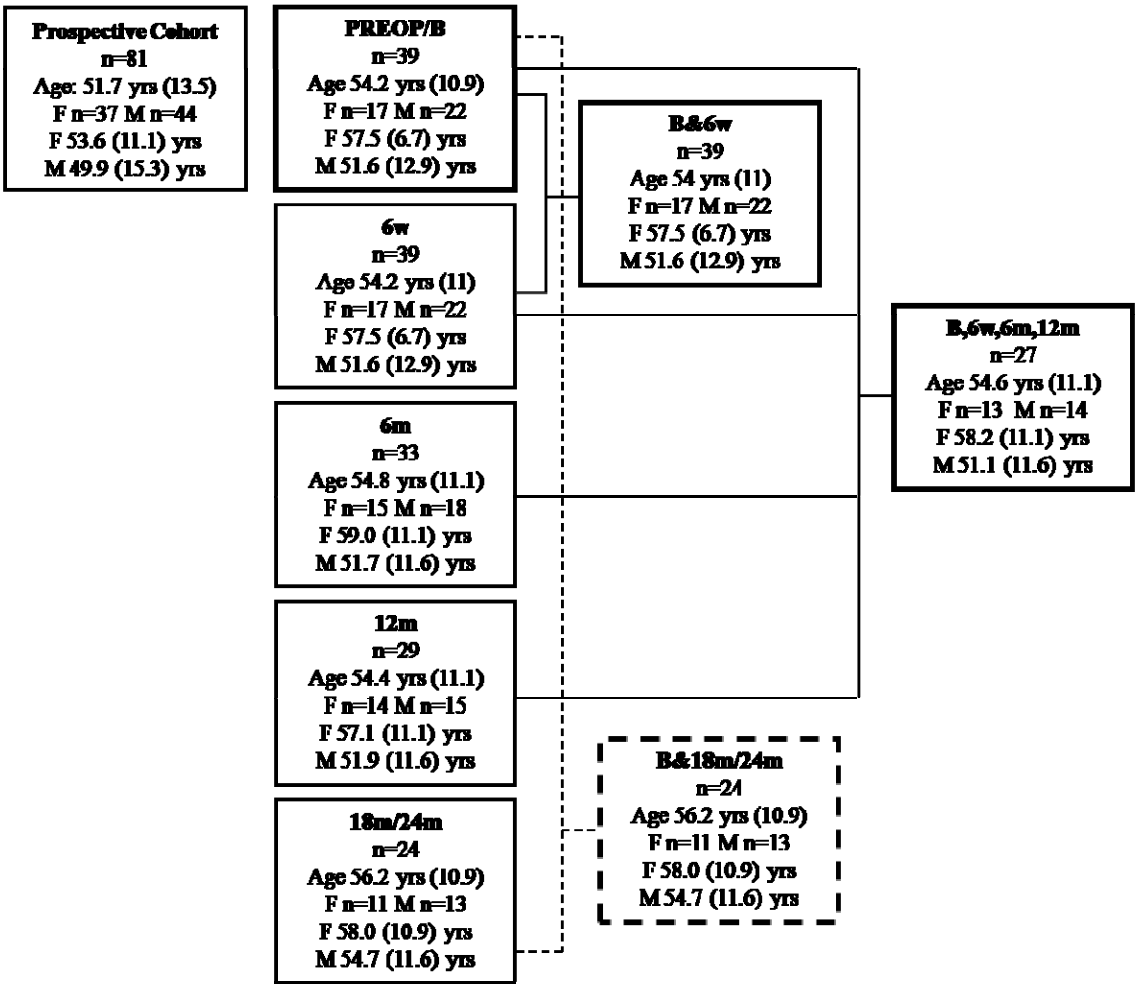


Figure 3.2: Organisation chart indicating the number of subjects whose surface curvature was assessed with rasterstereography over a two-year period. Subject numbers assessed at each time-point plus mean (SD) age and gender demographics for each are indicated.

Rasterstereography: Video rasterstereography was employed to derive: maximum lordosis (LL) spanning the thoracolumbar (ITL) to the lumbosacral inflexion points (ILS); maximum kyphosis (TK) spanning the cervicothoracic (ICT) to the ITL; pelvic incidence (PI) indicating the angle of the ILS in relation to the vertical (in lateral projection); and thoracolumbar sagittal balance (SB) which was mathematically calculated from values obtained for trunk inclination and trunk length. Trunk length (VP-DM) was defined as the vertical distance between the vertebral prominens (VP) and the left-right dimples midline (DM). Trunk inclination refers to the angle (in lateral projection) between the line of gravity and the line connecting the anatomical landmarks VP and DM. The angle is positive with VP anterior to DM (typical in forward leaning) and negative with VP posterior to DM (leaning backward). Two additional variables were assessed in the surgical cases: the depth (in the horizontal plane) of the lumbar curvature as defined between the ITL and ILS, and the ratio of TK divided by the LL. The system references an internal vertical (line of gravity) based on the instrument's position in relation to its base. Four feet on the base were manually adjusted to achieve level as determined from their integrated spirit levels. The features of spinal curvature of interest in this investigation were photogrammetrically derived via contours and anatomical landmark recognition based on the subject's posterior back surface (Drerup and Hierholzer 1987b) (refer to Chapter 2.3).

Figure 3.3 illustrates the method for obtaining data based on the sagittal projection produced via the rasterstereographic system. Sagittal profile reports for each individual's trials were printed to hard copy at the completion of each 5-trial set within a session. Relevant data was extracted from the reports and input into an Excel spreadsheet according to a unique subject code referenced to the time-point assessed.

Accepting rasterstereography-derived landmarks: It was anticipated that potential for error existed in accepting the system derived landmarks across time-points for the 2-year follow-up period. Practically, landmark data-point manipulation was only necessary when the system either failed to identify a landmark or made a gross obvious error in doing so. This aspect of the methodology had the potential to contribute to variation in landmark positioning and was identified to represent a possible limitation of rasterstereography-based serial assessment of surface curvature using the intended method. The rasterstereography feature of automatic landmark identification was therefore explored further in Appendix VI.1, which indicated the potential for variability in detecting landmarks within the same session in vivo. To mitigate any differences in the placement of landmarks over time and based on the results of the findings reported in Appendices VI.1&VI.2, the author used the printouts obtained at baseline as a semi quantitative audit-of the accuracy of the placement of fiducial points. This was based on an assumption that each individual's actual surface landmarks were relatively precisely located over time, despite inter-individual differences in adults (Stonelake et al. 1988).

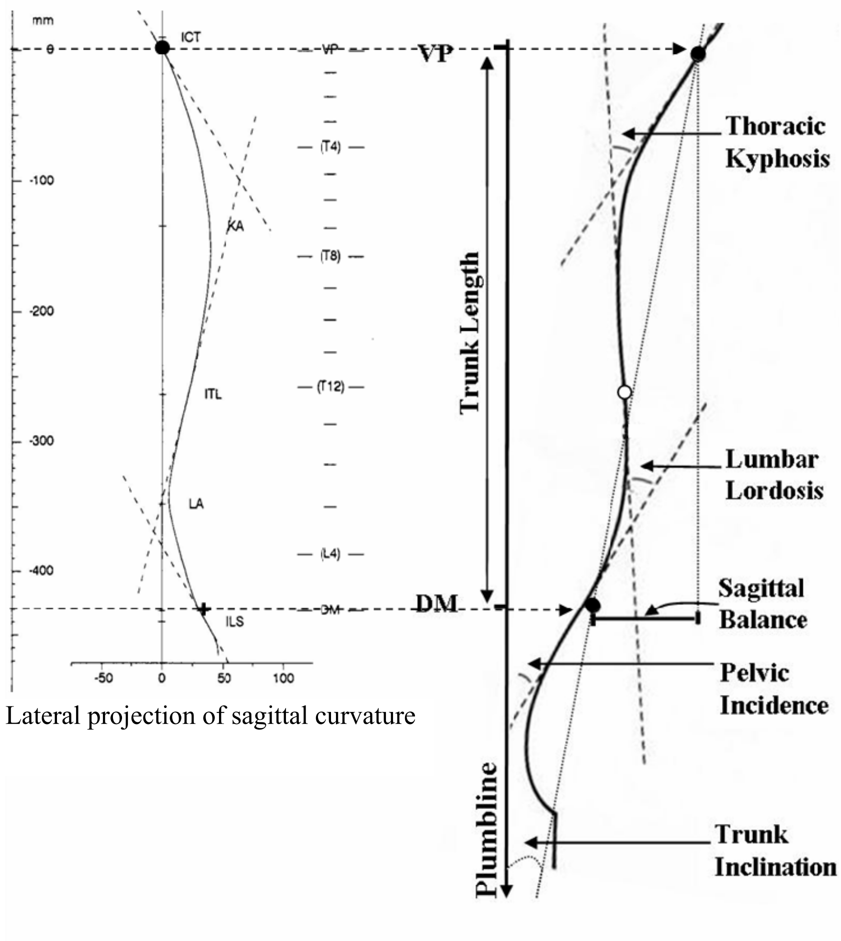


Figure 3.3: Schematic representation of how rasterstereography derives thoracic kyphosis (TK), lumbar lordosis (LL), pelvic incidence (PI), trunk inclination (TI) and trunk length (TL) based on a computed 2D sagittal lateral projection (also presented in Figure 2.14). TK represents the angle made by the cervicothoracic (ICT) and thoracolumbar (ITL) inflexion tangents. LL is derived from the angle between the ITL and lumbosacral inflexion (ILS) tangents. PI relates to the angle between the ISL and the vertical, while TI is defined by the angle formed by the intersection of the line joining the vertebral prominens (VP) and dimple midline (DM) with the vertical. TL is the vertical distance between VP and DM. Sagittal balance (mm) = TL(tanTI).

Statistical Analysis - Surgical:

Missed data: Missing rasterstereography time-point data occurred when patients: were unable to attend for assessment due to either their absence from the metropolitan area, illness (back-related or comorbidity) or apathy; or were excluded from follow-up as a result of requiring additional lumbar surgery, either as a revision of DIAM implantation, or progression to disc replacement, laminectomy or interbody fusion. No imputation methods (Twisk and deVente 2002; Shao and Zhong 2003) were considered appropriate to substitute for missed date, yet the retention of as many cases to their study end-point as possible was considered important for comparisons compared to baseline. As such, available data for each case was included for statistical analysis as outlined below.

Data treatment: Surface curvature outcomes were analysed in an exploratory manner based on the observational nature of the investigation. As such, the intention was to analyse data sets with varied n samples in order to maximise use of the available time-point data. Data were analysed using Microsoft Excel 2007 and StatView (Abacus Concepts, Inc., Berkley, CA, 1992). Descriptive statistics were derived for demographic and baseline rasterstereography variables. Mean values achieved for the surgical cases preoperatively were assessed against the baseline intra-session means for the healthy cases, using unpaired comparisons. Line charts for individual case data were displayed and included available subject information to depict observed serial effects for the entire surgical rasterstereography cohort for whom baseline and at least one of either the six weeks, one or two year postoperative time-point data were available (n=39). Paired comparison (n=39) of datasets at baseline and six weeks postoperatively provided the earliest estimate of changes following surgery (Figure 3.2). This complete series served to describe effects in the early postoperative period as an extension of the preliminary subset results reported in Chapter 6 (Crawford et al. 2009b). Similarly, for the 24 cases that had 18 or 24 month postoperative data, paired t-tests were used to define change from baseline. Box-plots were used to summarise the serial data for all cases with baseline, 6 week, 6 month and one year postoperative data (n=27) for each variable. Repeated ANOVA (with Scheffe's post-hoc test) was used to analyse serial changes in cases with complete year data. Serial group results for each variable were split according their gender, age group (≤50yrs>), DIAM primary implant level, number of DIAMs implanted, size of primary DIAM, anatomical, and diagnostic preoperative categorisations. Selected aspects of these analyses are also presented using box-plots. Associations between variables at baseline and as change scores over time were indicated with Pearson's correlation coefficients, based on the results of the 39 cases with preoperative and 6 week data, and the 27 cases for which one year time-point data was available. Statistical significance was defined as $p<0.05$ to represent a meaningful difference.

Repeatability of the measurement technique: Aspects of the intrinsic system repeatability of rasterstereography as reported by the developers of the instrument were outlined in Chapter 2.3. Chapters 5 & 6 present repeatability results for the system, based on measurements of the thermoplastic back phantom. Additionally, the studies described in Appendices VI.1&2, report intra- and inter-session variability in rasterstereographic sagittal outputs and therefore inform the potential for methodological errors in deriving data. The relevant appendices are cross-referenced in the associated chapters.

Additional methodologic details as they pertain to specific aspects of the study are explained further within the relevant results chapters: healthy subjects and the back phantom (Chapter 5), and surgical subjects (Chapter 8).

3.7.4 Radiographic method for assessing skeletal curvature

Evaluation of skeletal lumbar curvature and alignment was achieved based on erect standing plain lateral radiographs that were performed preoperatively, then at 6 weeks, and 12 months postoperatively. The radiographic procedure was applied to the surgical cohort as a component of their routine work-up for assessing alignment. Imaging was performed by radiographers at various Perth metropolitan private clinics, which were selected by the patients after written referral from the surgeon. Allowing the patient's choice of radiographic clinic site conformed to the surgeon's regular protocol and therefore reflected a clinical reality, while also aiming to limit subject burden in the attempt to optimise their retention in the study.

Patient cohort: Of the 81 patients followed in the prospective arm of the main study, 62 cases (27 females, 35 males) had suitable pre-operative radiographs from which to make comparisons. Inclusion criteria for this part of the outcomes analysis were derived from the existence and quality of at least two images per subject. A readable preoperative image was mandatory (n=62), in addition to one or preferably both of the 6 week (n=59) or 12 month (n=43) postoperative films. Cases who had all three images from the preoperative baseline, 6 weeks and 12 months postoperative time-points were included for serial comparison (n=40). Compared to the entire prospective cohort of 81 cases, the 62 subjects reported at baseline in this radiographic study were not significantly different in terms of gender proportion and mean age to the main group. Figure 3.4 outlines the numbers of subjects in which useful radiographic images were available per time-point, according to age and gender.

Patient positioning: In order to assist comparison of x-ray images at different time-points, radiographers at each site were advised to use a standardised technique for these cases based on guidelines provided by the author. Guidelines were added with each patient's radiography referral from the surgeon, which has been included as Appendix IV. Patients were instructed to stand wearing a gown and without footwear in the relaxed 'clavicle' position with their hands lightly clenched and placed over ipsilateral clavicles (Figure 3.5). This position has been reported to afford superior visualisation of key lumbar vertebral landmarks (Horton et al. 2005). Radiographers were asked to use a 100cm film-tube distance where possible, with the image centred at L3 and using a consistent left or right side patient stance.

Image assessment: Assessments of skeletal curvature involved identifying key vertebral landmarks from each individual's erect standing lateral radiograph. Radiographic images were produced in digital (JPEG) format at 1200dpi and viewed on a PC with external lighting dimmed to accentuate morphologic features. A 42cm LG Flatron L1915S monitor was used and each image was magnified to visualise one vertebral segment per screen, including two adjacent vertebral bodies and their intervening disc. A measuring programme employing Microsoft Excel

2007 and Visual Basic macro functionality was purpose-designed for the study and used to quantify radiographic parameters via mathematical algorithms (Mina 2008).

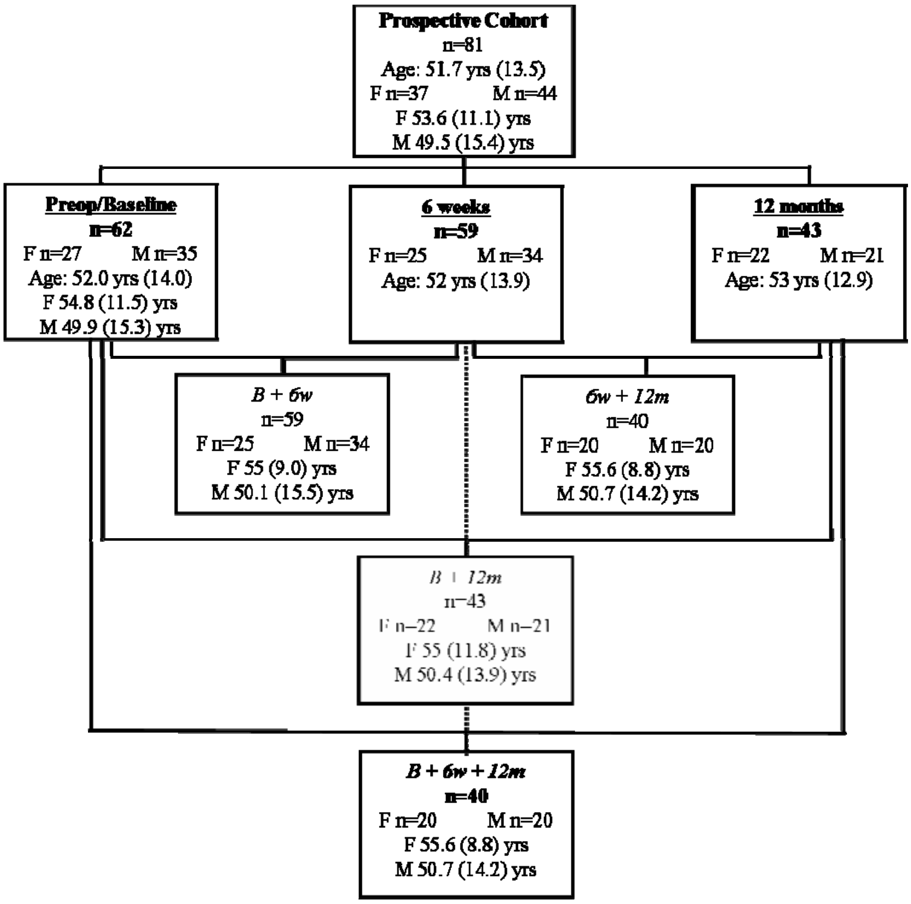


Figure 3.4: Organisation chart indicating the number of subject images available and used for comparisons between time-points. Age and gender demographics of each data set are indicated. Data are expressed as Mean (SD).

The author carried out all radiographic morphometric measurements. The constrained modified Cobb technique remains the most popularly used in the assessment of lumbar regional curvature (as indicated in Table 2.9) and was selected for use in the present study where radiographic imaging was limited to the lumbar spine. The present investigation followed a proportion of patients who received lumbar surgery, where the ISP device was implanted at the L5-S1 level. Consequently, the superior endplate of S1 was selected as the lower limit for reporting regional curvature. The superior endplate of L1 was selected as the upper limit, where L1 was identified as the fifth lumbar vertebrae positioned cephalad to the sacrum. Vertebral landmarks were visually identified and a vertebral corner 4-point placement method was employed based on the original 4-point method of Farfan (1973) (previously outlined in Table 2.11).

Lumbar vertebral bodies from L1 to S1 were marked at their four corners using a hand-held mouse with a customised cursor. Vertebral bodies were marked in a consistent order starting with the anterior superior corner, followed by the posterior superior corner, the posterior inferior corner and finishing with the anterior inferior corner (Figure 3.6 [A]). Only the sacral base (superior end-plate of the sacrum) was used to subsequently derive measurements, and as such less importance was applied to identifying the inferior sacral points when the distinction from the second sacral vertebrae was poor.

Figure 3.5: Patient positioning for radiographic imaging modelled using the 'clavicle' position as described by Horton et al (2005). In the clinical study, the surgical cases were attired in a loose gown and underwear. They were imaged without footwear.

Subsequent to each corner being identified, the programme automatically inserted lines joining the points, resulting in a quadrilateral model of each vertebra. The measurement programme allowed for manipulation of point placements once they had been made, which could be altered to best define the vertebrae (Mina 2008). Defining each vertebral body was achieved according to Genant's method as presented earlier (Spencer et al. 1990). Aspects of this are described further below. In the presence of abnormal osteophytic lipping, the intersection of the vertical and horizontal surface planes of the vertebral body cortex was used to demarcate a corner (Figure 3.6 [B]). Where vertebral surface concavity made the identification of vertical and horizontal planes difficult, a line that approximately defined the mid-plane of the vertebra was employed to guide point placement. If the view was not truly lateral (as in the case of a rotated segment), mid-plane approximate lines were identified to define each border and associated corner points (Figure 3.6 [C]). Artifacts of the error-of-parallax were accounted for by normalising the vertebral body dimensions according to the two previous descriptions (Figure 3.6 [D]). Data-point sets for each image were saved as a .TXT file according to a unique patient code and the relevant time-point. Skeletal variables were computed from the X-Y point coordinates using an Excel-based macro-enabled programme.

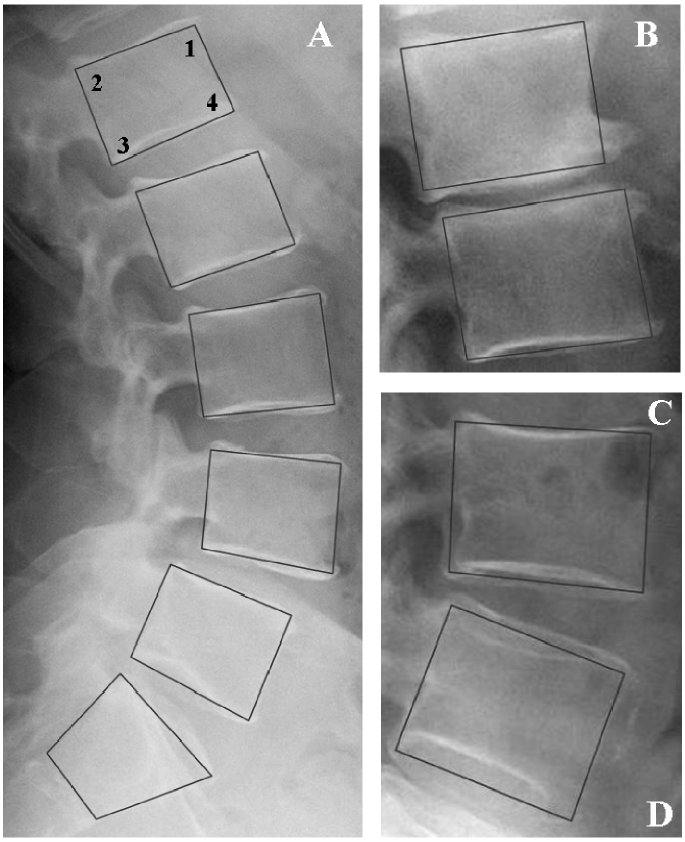


Figure 3.6: Composite schematic illustration revealing the 4-point method used to define lumbosacral vertebral corners on a digital radiographic image (A). The treatment of examples with: osteophytic lipping (B); vertebral surface concavity and a rotated vertebral body (C); and error of parallax artefact (D) are outlined.

Determination of radiographic variables: The radiographic variables assessed in this study included: lumbar lordosis (LL); sacral inclination (SI); disc angles [at the primary surgical level (PDA), and the level above (supradjacent) (SDA)]; regional sagittal balance (RSB); RSB relative to the length of the lumbar region (RRSB); and mean radius of curvature (RoC) [for the entire lumbar region (RoC1-6) and that local to the primary implant (RoC2+2)]. The methods employed for each of these variables are outlined below and presented schematically in Figures 3.7 and 3.8.

Lumbar Lordosis: Lumbar lordosis (LL; θ_C) was defined via the constrained modified Cobb method (Singer et al. 1994; Harrison et al. 2001) by using the superior end-plates of L1 and S1 for reference to provide two intersecting tangents [Figure 3.7 (A)].

Sacral Inclination: Sacral inclination (SI; θ_S) was defined by the angle created between the sacral base and the horizontal [Figure 3.7 (B)].

Disc Angles: Disc angle (PDA; θ_1) at the single or primary pathological level implanted with a DIAM was recorded as the intersection of the tangents of the inferior end-plate of the upper vertebra, and the superior end-plate of the lower vertebra (Stagnara 1982). The supradjacent disc angle (SDA) was measured in the same way but referred to the disc one level above the primary implanted level [Figure 3.7 (B)].

Regional sagittal balance: Defining sagittal balance for the lumbar region (RSB) involved using the L1 axis S1 distance (LASD) as described by Kawakami et al (2002). This method reports the distance in the horizontal plane between the vertical line from the centroid of L1 and the posterior superior corner of the sacrum. Relative regional sagittal balance (RRSB) was calculated as RSB divided by the length of the lumbar spine (as measured between the centroid of L1 and the posterior superior sacral corner) [Figure 3.7 (D)]. The units of measure for RSB and RRSB are explained later in relation to standardising for magnification. Their units of measure are reported as relative-millimetres (Rmm).

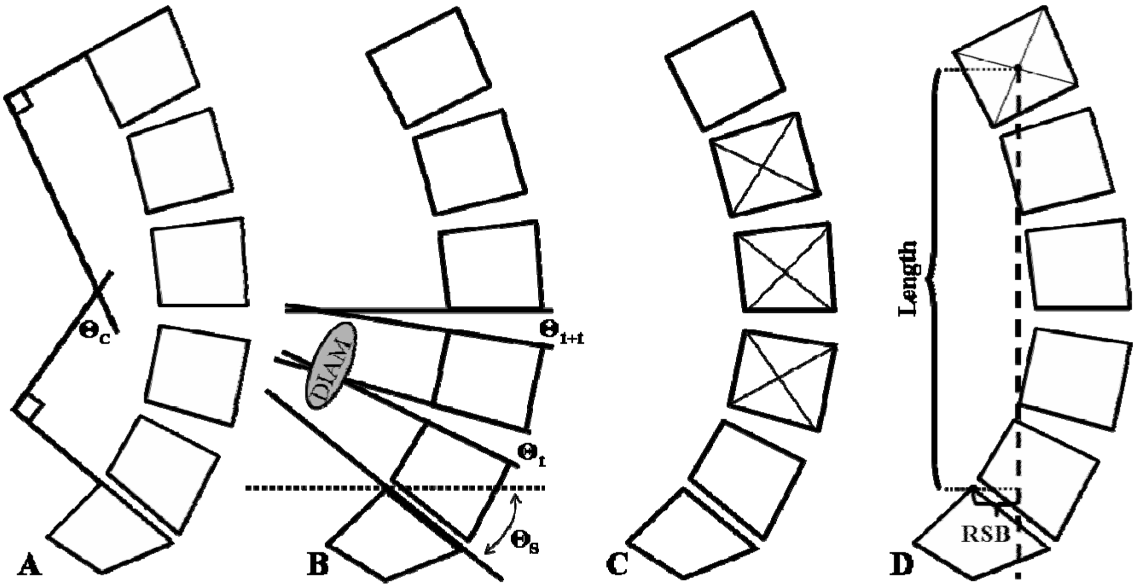


Figure 3.7: Schematic representation of the methods employed to derive: lumbar lordosis (θC) (A); sacral inclination (θS) and disc angle at the primary DIAM-implanted ($\theta 1$) and supradjacent ($\theta 1+1$) spinal segments (B); correction factor scaled according to the combined areas of L2-4 from the baseline preoperative image (C); and regional sagittal balance (RSB) as measured in the horizontal plane. RRSB=RSB/length of the lumbar region.

Radius of curvature: The mean radius of curvature for the lumbar spine (RoC1-6) was represented by a least squares fit circle using the dataset of the midpoints of each included endplate between the superior end plates of L1 and S1. This approach represented a modification of that described by Singer et al (1994) for the thoracic spine. Since each radiograph included an unknown magnification factor, the resultant radius was presented as a relative distance according to system references. Radius of curvature local to the primary DIAM-implanted level (RoC2+2) was similarly derived by referencing the centre of the endplates constituting two vertebrae both above and below the index level. When the primary implant level was at L4/5 or L5/S1, the centre of the S1 superior end plate represented the lowest reference point [Figure 3.8].

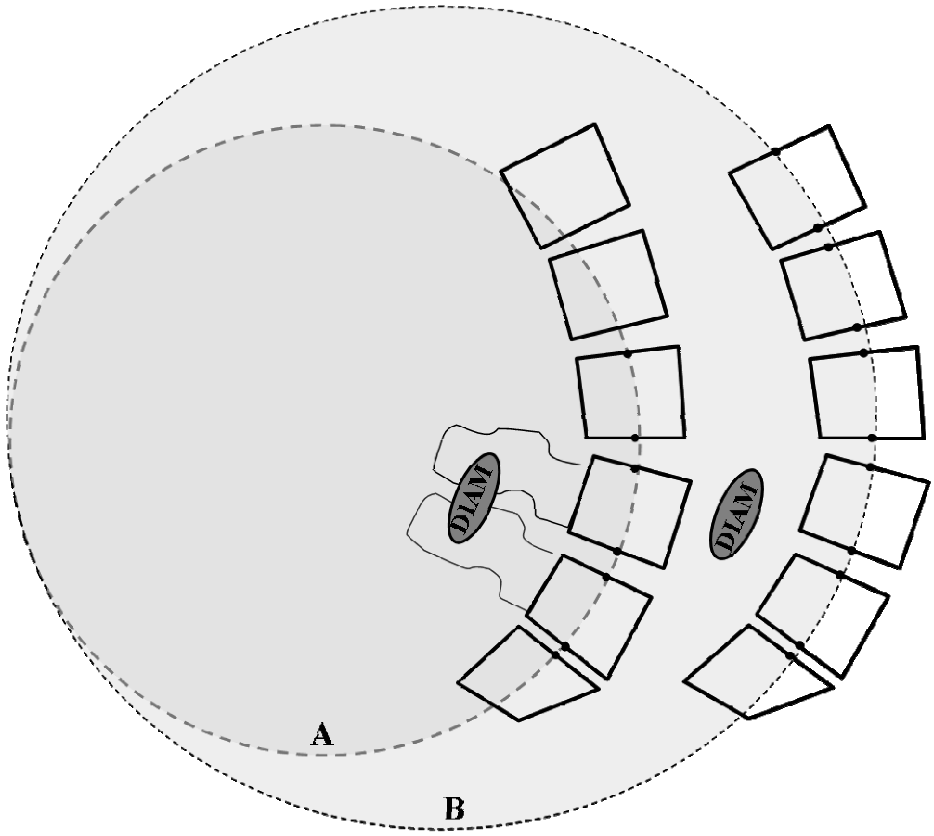


Figure 3.8: Schematic representation of the method employed to derive radius of curvature (RoC) for a subject where the index DIAM level is L4-5. RoC local to the primary implanted level (RoC2+2) (A) and for the entire lumbar region (RoC1-6) (B), are depicted to indicate the least squares fitted circle approximating the curve made by the vertebral endplate midpoints.

Measurement standardisation: Correction for differences in magnification between serial radiographs for each subject was necessary for the non-angular variables of regional sagittal balance and radius of curvature. As one guideline for radiographic imaging was to centre at the L3 vertebral body, the projected areas of the L2, L3 and L4 vertebral bodies were employed to calculate the correction factor. Ratios between the postoperative and preoperative films were scaled according to the square root of the combined L2-4 vertebral body areas of the baseline image. Given the unknown actual magnification of each image, RSB and RoC variables could not be expressed as a metric and instead were reported according to system references [Figure 3.7 (C)]. Both are reported in system-relative millimeters (Rmm).

Statistical Analysis: Skeletal curvature outcomes were analysed in an exploratory manner based on the observational nature of the investigation. As such, the intention was to analyse datasets with varied n samples in order to maximise use of the available time-point data. Data were analysed using Microsoft Excel 2007 and StatView (Abacus Concepts, Inc., Berkley, CA, 1992). Descriptive statistics were derived for demographic and baseline radiographic variables to assess the mean and standard deviation for the 62 cases comprising the baseline cohort. Line charts for individual case data where all three time-points were available were used to depict observed serial effects for the entire cohort. Box-plots were used to summarise the serial data for all cases with baseline, 6 week and 12 month postoperative data (n=40). Serial group results for each variable were split according their gender, age group (≤50yrs>), DIAM primary implant level, number of DIAMs implanted, size of primary DIAM, anatomical, and diagnostic preoperative categorisations.

The primary disc angle (PDA) results for a subset of cases that received a single DIAM (n=22) were separately analysed. Repeated ANOVA (with Scheffe's post-hoc test) was employed to test for serial change where all three time-point measures were available. In order to analyse the maximum sets of case data available at two time-points, paired two-tail t-tests (for means) were used to assess the significance of any change between two time-points in the radiography-derived parameters (B-6w: n=59; B-12m: n=43; 6w-12m: n=40). Emphasis was placed on the results showing significant change as derived from serial analysis using repeated ANOVA via Scheffe's post-hoc test. Associations between variables at baseline or as change scores over time were indicated with Pearson's correlation coefficients, based on the results of the 40 cases for which all time-point data was available. Statistical significance was defined as $p<0.05$ to represent a meaningful difference.

Repeatability of the measurement technique: Repeatability of the values derived from the same radiograph was assessed through repeated measurements of ten surgical cases' baseline images. The ten images were processed separately according to the image assessment protocol described earlier, and then repeated a week later. Duplicate data were employed to indicate intra-rater error of the author included in re-digitising each JPEG image using the custom programme. Results for intra-rater repeatability were analysed for the mean and standard deviation of differences for each radiographic variable employed in the study are presented in Table 3.1.

Table 3.1: Differences between two repeat measurements of the same baseline plain lateral radiographic image for ten surgical cases. Images were processed according to the described using the described 4-point data placement method, on two occasions one week apart. This analysis was employed to assess the intra-rater reliability of image processing.

	Test 1	Test 2	Difference	2-tail t-test
Lumbar Lordosis (˚)	57.1 (11.4)	57.0 (12.2)	-0.15 (2.32)	p=0.86
Sacral Inclination (˚)	37.4 (5.2)	37.3 (6.2)	0.07 (1.56)	p=0.90
Primary Disc Angle (˚)	15.6 (6.8)	16.1 (7.5)	0.50 (1.09)	p=0.20
Regional Sagittal Balance (Rmm)	2.3 (27.9)	2.0 (27.5)	0.31 (1.92)	p=0.62

3.7.5 Interactions between outcome variables: HRQoL, surface, and skeletal curvature

To avoid repetition, descriptions of the methods employed in comparing the clinical outcomes examined in this thesis investigation, are presented in Chapter 8.

3.8 Summary

This chapter has provided description of the methodological aspects of the thesis relating to the: design; hypotheses; subject recruitment; sequence of tests for the prospective phase; clinical outcomes measure for the retrospective phase; clinical outcome measures for the prospective phase, including the patient demographics, HRQoL questionnaire, rasterstereographic assessment of surface thoracolumbar curvature, and radiographic assessment of skeletal lumbar curvature.

CHAPTER 4

Clinical outcomes following lumbar surgery augmented with DIAM interspinous implant

4.1 Introduction

This chapter presents the published results of the retrospective arm of the main investigation (Crawford et al. 2009a), which reflects the earliest stage of thesis development. Consequently, references to literature within the text relate to those existing prior to the papers' submission in January 2009. Contents of the complete paper have been truncated to reduce repetition of introductory literature that has already been presented in Chapter 2. Methods, results, discussion and conclusions have been retained to indicate the process and contribution that Phase I played in the formative stage of the main prospective arm of the study.

Despite preliminary clinical results being reported for the DIAM at recent international neurosurgical conferences (Iob et al. 2001; Lam et al. 2005; Fabrizi et al. 2006; Iob et al. 2006; Alvaro et al. 2008), few studies on either its efficacy or effectiveness appear in the literature, and are limited to retrospective investigations (Caserta et al. 2002; Mariottini et al. 2005; Kim et al. 2007; Taylor et al. 2007) and two biomechanical cadaveric analyses (Phillips et al. 2006; Wilke et al. 2008). Table 4.1 provides a comparative summary of the clinical literature reporting on the DIAM. Based on this literature, the primary hypotheses for this retrospective phase were that: lumbar surgery augmented with DIAM results in improved back and leg pain, function, general well being and satisfaction than at preoperative baseline using accepted definitions for MCID; and that patients who undergo the addition of a DIAM interspinous implant in treatment of predominant zygapophysial joint dysfunction will have improved outcomes over those with discogenic pathologies.

4.2 Methods

Prospectively collected patient-based outcomes data from a single private neurosurgical practice are reported for 39 patients (21 females, 18 males; mean age 51, range 23-85 years) who underwent lumbar surgery augmented with the DIAM. Surgery was indicated for segmental lumbar disease after: imaging confirmed diagnosis, symptom duration > 12 weeks, and failed conservative management (including pain management interventions like rhizotomy procedures and/or intradiscal injections where indicated).

Table 4.1: Comparison of studies reporting outcomes following lumbar surgery augmented with the Device for Intervertebral Assisted Motion (DIAM).

Author, Year	**Sample**	**Conditions (cases)**	**Surgery (cases)**	**1° Measures**	**Follow-up**	**Findings (cases)**
Present Study	39; 21F, 18M; 51yrs (23-85)	Anatomical: disc (25); facet (14). Nerve root compression (11); Facet Joint Pain (7); Segmental Instability (21)	Augmentation (39)	MODEMS: Pain; ODI; Satisfaction	B; 6w; 3, 6, 12, 24m	Improvement best at 6m: Pain 23.4%; ODI 13.5%. Facets better than discs
(Silva et al. 2007)*	30; 11F,19M; 38yrs (18-55)	Adjacent to fusion (12); Disc herniation (9); Re-discectomy (9)	Augmentation (30)	Japanese Orthopaedic Assessment	Various: >12m	25% = Fair improvement
(Kim et al. 2007)	31; 15F,16M; 51yrs (27-74)	Recurrent disc herniation; Large disc herniation with radiculopathy; Spinal stenosis	Augmentation (31): Compared with decompression alone	VAS (Back and leg pain); modified Macnab	B; Day1; 1 week; 3m; 12m (mean)	Improvement due to decompressive surgery only
(Taylor et al. 2007)	104; 49F,55M; 51yrs (25-86)	Herniated disc (60); disc disease (42); OA foraminal stenosis (37); soft stenosis (6); bulging disc (2)	Isolated (9); Augmentation (95)	Dallas Pain Questionnaire; Incidence data	B; 6m; 18m	(92/104) relieved
(Fabrizi et al. 2006)*	1100; n/a; 53yrs (18-86)	Black disc-facet (395); Soft and/or foraminal stenosis (455); Large disc herniation (101); Topping-off (149)	Single level (715); Double level (352); >2 levels (33)	VAS-Satisfaction	Various: mean 36m (12-60m)	Very satisfied (53%); satisfied (41%); No change (5%); Worse (1%)
(Lam et al. 2005)*	100; n/a	n/a	n/a	VAS; SF-36; Incidence data	Various: B; 12-36m	Good-Excellent (undefined)
(Mariottini et al. 2005)	43; 17F,26M; 54yrs (34-80)	Soft stenosis (36); Canal stenosis (7); Mild instability (23/43)	Augmentation (43); Single level (31)	Dallas Pain Questionnaire; Henderson Classification	Various: 12m-5yrs	Excellent (18); Good (22); Neutral (3)
(Schiavone and Pasquale 2003)	42: 22 DIAM alone: 9F,13M; (31-51yrs)	Disc segment degenerative disease	Isolated (22); Augmented pedicular synthesis (20)	Excellent, Good, Fair, Poor Rating scale	Various: mean 10m	Excellent (16); Good (4); Fair (2); Poor (0)
(Caserta et al. 2002)	82; n/a; 43yrs (n/a)	Degenerative disc disease (41); Disc herniation (21); Recurrent disc herniation (9); Instability (5); Spondylolisthesis (2); Stenosis (4)	Isolated stabilisation (57) & laminectomy (4/57); Combined (fusion) stabilisation (25)	Not declared	Various: mean 20m (1-6yrs) for 61/82 only	Satisfactory
(Iob et al. 2001)*	27; 15F, 12M; n/a (36-74)	Failed back surgery: Foraminal stenosis & degenerative instability (20); Iatrogenic instability (2); Recurrent disc herniation (4); Arachnoiditis (1)	Single level (25)	Not declared	12m	(19/27) relieved

* denotes poster or conference proceedings abstract. Sample = [n; F/M; mean age (range)]. VAS = visual analogue scale. B = preoperative baseline. ODI = Oswestry Disability Index

Consecutive patients were recruited between February 2005 and July 2006. Enrolment criteria required demographic, surgical and clinical outcomes data from the preoperative baseline through to 24 months postoperatively. Informed consent for follow-up study was obtained from all subjects pre-operatively. University institutional ethics approval was obtained for this investigation.

Subject demographics: Demographic data for gender, age (at surgery) and presence of comorbidities were collected. The segmental level(s) of DIAM surgery were recorded for each case along with data regarding concurrent operative procedures. Patients were diagnosed preoperatively by the collaborating neurosurgeon and categorised for this study in two ways: by anatomical involvement, and by the primary clinical diagnosis. The two anatomical categories were: predominant facet involvement (facet), or disc disease. Diagnostic indications were primary: nerve root compression syndrome (NRC), facet joint pain syndrome (FJP), or segmental instability (SI). From an original patient cohort of 101 cases, patients diagnosed with central canal stenosis, those receiving 4 or more implants, and those with incomplete serial data, were excluded from the study to reduce confounders. Both one- and two-levels were implanted with a DIAM in 16 cases, with 7 cases that received 3 implants. Implantation of the DIAM was not performed as an isolated surgery; the other associated minimally invasive procedures included: laminotomy (17/39); microdiscectomy (14/39) and interlaminar central and lateral recess decompression (8/39).

HRQoL outcomes: Subjects completed the Musculoskeletal Outcomes Data Evaluation and Management System (MODEMS) self-report health outcomes questionnaire at specific time-points: preoperative baseline, 6 weeks, 3, 6, 12 and 24 months postoperatively. Follow-up data were collected between February 2005 and July 2008 for: pain, back-specific function and satisfaction with symptoms. Pain data were derived from responses to questions regarding the frequency and bothersomeness of back and/or leg pain, where a score of 100% represented highest pain severity. This scale is based on the Sciatica Bothersome Index and has proven validity (Patrick et al. 1995; Walsh et al. 2003). Back-specific function was measured by the MODEMS version of the Oswestry Disability Index (ODI) (Daltroy et al. 1996), where higher values represented the greatest dysfunction. Patient satisfaction with symptoms was established using a 5-response scale in answer to the question “If you had to spend the rest of your life with the symptoms you have right now, how would you feel about it?” Subjects were rated as being more satisfied if their post-operative time-point response was an improvement along the scale compared to their baseline score (Deyo and Diehl 1986).

Missed data: In the event of missed data where either a subject omitted a response on the MODEMS questionnaire or failed to provide data at a time-point but had complete data thereafter, the last-value-carried-forward (LVCF) longitudinal imputation method was employed (Twisk and deVente 2002). All 39 subjects provided complete baseline data; only 8 data points were missing for the cohort over the 24-month period.

During the course of the study, 11 (of 39) patients underwent further lumbar surgery, which included: six DIAM re-sizing revisions; three lumbar interbody fusions; and two single-level disc arthroplasties. Data from their last available time-point, prior to their second (or revision) surgery, was projected forward to 24 months via the LCVF method.

Statistical analysis: Outcomes were described statistically, with serial data examined using repeated measures analysis of variance (Scheffé's post-hoc test). Statistical significance was defined as $p<0.05$ to represent meaningful differences.

4.3 Results

A total of 69 DIAM devices were implanted in the 39 cases with the most common level being L5/S1 (n=31) followed by L4/5 (n=26), L3/4 (n=10), and L2/3 (n=2). The primary levels implanted for the 39 individuals were L4/5 (n=18) and L5-S1 (n=18), with two at L3/4 and one at L2/3. The distribution for DIAM implant according to lumbar segment in this series is illustrated in Figure 4.1.

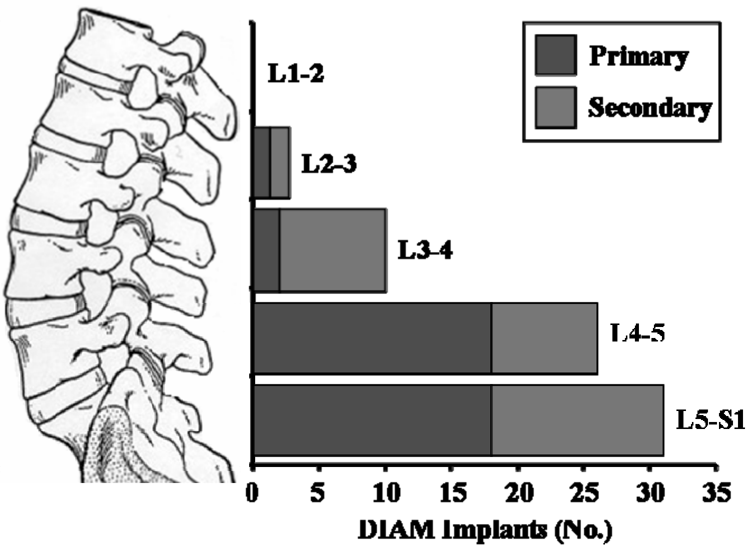


Figure 4.1: Location of primary and secondary DIAM implants according to lumbar segmental level in 39 individuals for treatment of varied lumbar spinal pathologies.

Categorisation showed primary involvement of disc in 25/39 cases and facet lumbar pathology in 14/39. Clinical indications for surgery were: segmental instability (n=21/39); nerve root compression (n=11/39); and facet joint pain syndrome (n=7/39) [Figure 4.2]. The distribution of cases according to both categorisations is represented in Table 4.2.

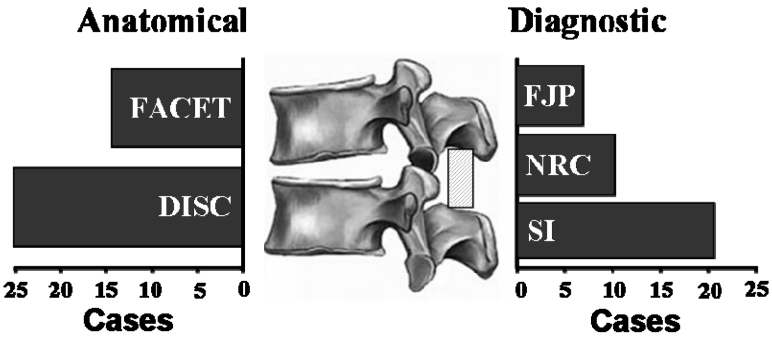


Figure 4.2: Categorisation of 39 patients receiving lumbar surgery augmented with a DIAM interspinous implant according to disc, or facet disease. Diagnostic categorisation comprised: facet joint pain syndrome (FJP), nerve root compression (NRC), or segmental instability (SI).

Table 4.2: Case distribution according to anatomical (facet or disc) and diagnosis (facet joint pain (FJP); nerve root compression (NRC); and segmental instability (SI)) categories, for 39 subjects who received lumbar surgery augmented with the DIAM interspinous implant.

	FJP	**NRC**	**SI**	**n**
Facet	7	6	1	14
Disc	0	5	20	25
n	7	11	21	39

Significant baseline improvement for pain and back-specific function was confirmed at all but one time-point (function at 6 weeks; *p=0.06*) post surgery, with the greatest improvement achieved at six months post-operatively ($p<0.05$) (Table 4.3). This reflected a 23.4% and 13.5% group reduction in pain and back-specific function, respectively. Table 4.3 presents the descriptive statistics for pain and function at all time-points. When the patient cohort was categorised according to anatomical involvement, significant improvement was only evident in those with facet pathology, where the greatest reduction in pain and improvement in back-specific function was most evident by the 3-month postoperative time-point (Table 4.3).

Figure 4.3 represents changes to pain and back-specific function, seen in the cohort and according to anatomical groups. Figure 4.4 presents pain and back-specific function changes as they relate to subjects' clinical diagnosis. Patients receiving the DIAM-augmented surgery in treatment of nerve root compression (n=11) or facet joint pain syndrome (n=7) (Figure 4.4) appeared to demonstrate deteriorating pain from 3 months out to two years postoperatively. By 12 months post-operatively, 19 of the 28 patients who had not received additional lumbar surgery were more satisfied with their symptoms than pre-operatively. Sixteen subjects reported satisfaction both at 12 and 24 months, with 8 having improvement to their satisfaction with symptoms between these final two time-points.

Table 4.3: Pain and Function outcomes over 24 months for 39 patients following lumbar surgery augmented with a DIAM interspinous implant. Mean ($\bar{\mathbf{x}}$), standard deviation (SD), mean difference between Baseline and post-op time-point ($\bar{\mathbf{x}}$ Diff), and significance of $\bar{\mathbf{x}}$ Diff (Scheffé's post-hoc) are revealed for all cases (Group), and split by category (Disc or Facet).

	Time	**Group (n=39)**				**Disc (n=25)**				**Facet (n=14)**			
		Mean	SD	$\bar{\mathbf{x}}$ Diff	ρ-value	Mean	SD	$\bar{\mathbf{x}}$ Diff	ρ-value	Mean	SD	$\bar{\mathbf{x}}$ Diff	ρ-value
Pain	B	77.9	20.4			72.8	23.4			86.9	8.5		
	6 w	56.6	22.9	21.3	<0.0001*	60.7	23.3	12.2	0.20	49.4	21.1	37.5	<0.0001*
	3 m	54.8	23.4	23.1	<0.0001*	58.7	25.5	14.2	0.08	47.9	17.8	39.0	<0.0001*
	6 m	54.5	23.6	23.4	<0.0001*	57.2	26.7	15.7	0.04*	49.7	16.6	37.2	<0.0001*
	12 m	56.8	24.2	21.1	<0.0001*	59.3	27.2	13.5	0.11	52.4	17.5	34.5	<0.0001*
	24 m	61.1	24.6	16.8	0.001*	63.5	26.1	9.3	0.50	56.8	21.9	30.1	<0.001*
Function	B	58.3	17.0			58.2	17.8			58.4	16.3		
	6 w	48.9	18.5	9.4	0.06	51.2	19.8	7.0	0.65	44.8	15.7	13.6	0.03*
	3 m	45.0	18.0	13.3	<0.001*	48.6	20.7	9.6	0.30	38.5	9.2	20.0	<0.001*
	6 m	44.8	17.8	13.5	<0.001*	47.5	20.2	10.7	0.18	40.1	11.3	18.4	0.001*
	12 m	45.2	16.8	13.1	<0.001*	48.1	19.2	10.1	0.24	39.9	10.1	18.5	<0.001*
	24 m	45.3	18.3	13.0	<0.001*	49.0	20.4	9.1	0.35	38.5	11.3	19.9	<0.001*

B=pre-operative baseline; 6w=six weeks post-op; 3m, 6m, 12m, 24m=3, 6, 12, 24 months post-op; Pain=MODEMS-derived pain scale (%); Function=Oswestry Disability Index (ODI MODEMS version)(%); *=significance of improvement

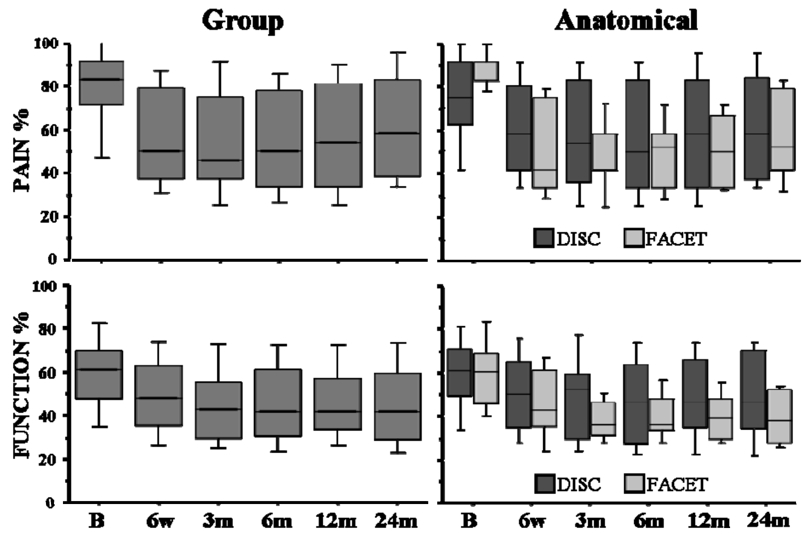


Figure 4.3: Outcomes over 24 months for pain and function in 39 patients who underwent lumbar surgery augmented with a DIAM interspinous implant. Results are displayed according to: all cases (Group); and anatomical categorisation [Anatomical; disc (n=25) or facet (n=14)]. Boxes represent range of the middle two quartiles; bar within the box the median, and whisker bars the 10th (lower) and 90th (upper) percentiles. Reduction represents a symptomatic improvement, which was significant ($p<0.05$) at all time-points compared to baseline [except function between baseline and six weeks ($p=0.06$)].

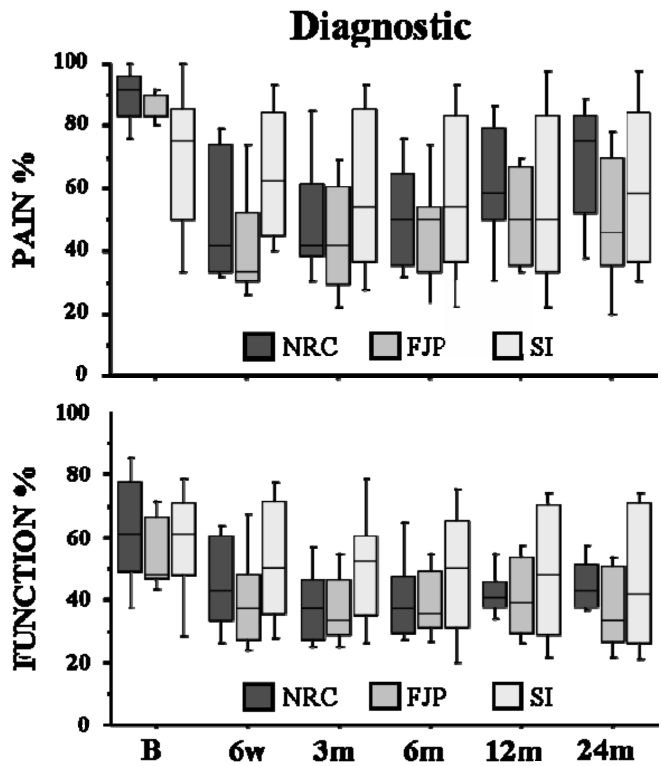


Figure 4.4: Outcomes over 24 months for pain and function in 39 patients who underwent lumbar surgery augmented with a DIAM interspinous implant according to diagnostic category. Clinical diagnoses (nerve root compression (NRC) n=11, facet joint pain syndrome (FJP) n=7, and segmental instability (SI) n=21) are compared. Boxes represent range of the middle two quartiles; bar within the box the median, and whisker bars the 10th (lower) and 90th (upper) percentiles.

4.4 Discussion

In general, patients with facet joint disease demonstrated more positive outcomes at 24 months following lumbar surgery augmented with DIAM, compared with those with disc pathology. The most prevalent DIAM-implanted level for this study was L5-S1, with that level plus L4-5 representing over two-thirds of the total surgeries. These results agree with incidence data on disc injury and facet joint pathology where there's an increase craniocaudally in the lumbar spine (Fujiwara et al. 1999). Previous investigations have reported fewer implants at the lumbosacral level with the majority being at L4-5 (Caserta et al. 2002; Schiavone and Pasquale 2003; Fabrizi et al. 2006; Kim et al. 2007; Taylor et al. 2007). Differences in the level of implant between the present study and previous trials may reflect varied clinical indications for surgery and/or refinements of the DIAM device and technique over time.

Results of this study revealed best improvement in pain and function after lumbar surgery augmented with DIAM interspinous implant by three to six months postoperatively. Improvement in back-specific function was typically maintained to 24-months post-operatively; however in this sample, pain gradually deteriorated between 6 and 24 months. This appeared more evident in those categorised with disc pathology, or nerve root compression. Acknowledging the limitations of this relatively small cohort, these results provide further insight as to pathologies that may respond to lumbar surgery augmented with DIAM. Further controlled investigations to examine responders and reasons for non-responsiveness appear warranted. Previous studies have described improvements in pain and function over extended timeframes post-DIAM (Table 4.1); however the present investigation elaborates changes over several intervals. Based on these observations, assessment at six-months post-operatively can provide an indication to later outcomes. The trend for deterioration seen for pain between 6 to 24 months in this series suggests a need for clinical effectiveness trials with extended follow-up beyond 2 years.

Additionally, the heterogeneous cohort investigated in this study and those studies reported in Table 4.1, make it difficult to discriminate the effect of the primary surgery from the role of the DIAM interspinous implant. A need for investigations assessing the effect of DIAM surgery on discreet lumbar pathologies remains. Distinguishing between the effects of the DIAM device in isolation or in combination with concurrent decompressive surgery will be necessary to better understand patient outcomes. Anatomical grouping to either primary disc, or posterior element pathologies, may provide further insight into response patterns after this form of combined lumbar surgery. Increased group numbers would provide improved power to allow for matching of primary pathology and clinical diagnoses.

In their study assessing the responsiveness of several outcome measures including MODEMS and the ODI, Walsh et al (2003) showed that pain scales were significantly more responsive than function scales. The MODEMS lumbar instrument pain scale, derived from questions relating to both back and leg (sciatica) frequency and bothersomeness, had the highest probability of correctly identifying patients' improvement. The present study revealed a best group improvement in pain of approximately 23%, which subsequently reduced to 17% by 24 months. Recent IMMPACT recommendations (Dworkin et al. 2008) suggest minimal clinically significant improvement of pain ranges between 10-20%, with improvements greater than 28% indicating meaningful gains. The group results in the present study therefore demonstrated a minimal clinically significant change to 24 months after surgery augmented with DIAM; however Table 4.3 indicates considerably better improvement ($p<0.001$) in those with facet pathology than those with discal disease. The results of this cohort study demonstrated progressive improvement in back-specific function as measured by the ODI (MODEMS). Based on minimally clinically important difference recommendations, where 10% reduction in ODI is considered a clinically demonstrable improvement (Hagg et al. 2003), this change was reached by 3 months and maintained at 24 months. Though an improvement in ODI was clearly demonstrated following DIAM surgery (Figure 4.3), closer inspection revealed that this was dependent on pathology; the trend was less clear for disc disease (Table 4.3).

Baseline measures for pain were more consistent in those categorised with facet dysfunction (refer to Fig. 4.3), and diagnosed with nerve root compression or facet joint pain syndrome (Fig. 4.4), than those with disc or segmental instability, respectively. The heterogeneity in the patients deemed appropriate for lumbar surgery augmented with DIAM, complicates any long term outcomes comparison. In clinical trials it is intuitively appropriate to compare cases with common features, yet in an effectiveness trial such as this; sub-group analysis is limited unless the study is powered appropriately. The superior response of patients in the facet subgroup may be expected when the proximity of the implant to the posterior elements is considered. The distraction imposed by the device in the interspinous space may unload the facet joints through a posterior migration of the centre of rotation at that segment. Cadaveric investigations have shown that the DIAM reduces facet loading by up to 50%, particularly in positions of extension (Phillips et al. 2006; Wilke et al. 2008). The poorer response of cases diagnosed with segmental instability may reflect the advanced stage of degeneration, which in turn implies a more chronic condition with a longer duration of symptoms, and involving more complex surgery. A further explanation for the poorer outcome in segmental instability relates to the nature of interspinous implants as non-fusion stabilising devices, where a compromise to stability for mobility is inherent in their design (Christie et al. 2005).

Excluding cases that required repeat lumbar surgery within the 2-year follow-up period, over half of the remaining patients (20 of 28) were more satisfied with their symptoms at 24 months when compared to baseline. This finding is consistent with the results of Kim et al (2007) who used a similar outcome measure. Results of the present study described clinical outcomes for a patient cohort who underwent lumbar surgery with DIAM interspinous implant for treatment of their lumbar segment disease. When applying these results to other lumbar spinal populations, several limitations should be considered. The participants for this investigation were sourced from a single neurosurgical practice resulting in a selected cohort whose surgical intervention augmented with DIAM was diagnosis-determined and non-randomised. Any potential bias can be weighed against the advantage of following cases from a single surgeon, which effectively controls the clinical decision-making for the group.

A number of patients (6/39) who had follow-up surgery received revision of their DIAM implant at the same level with one of greater size. Data management using the LVCF method (Twisk and deVente 2002) for these cases meant that a poor outcome was projected forward to their 24-month anniversary. Although device sizing was maximised at the time of surgical insertion, it is hypothesised that settling of the device and the bony contact of the cojacent spinous processes may occur in some patients, resulting in inadequate discal and posterior column unloading (observation of neurosurgical collaborator). The remaining repeat surgery cases (5/39) reflected three lumbar interbody fusions; and two single-level arthroplasties. The further surgery rate in this study was high, where 11 of 39 cases required additional lumbar surgery prior to trial completion. Taylor et al (2007) reported the need for repeat lumbar surgery in 11 of their 104 DIAM-implanted cases, with 5 of those requiring a new DIAM. The proportion of failed surgeries resulting in a revised DIAM implant was similar in Taylor's study and the present report. The variable cohorts makes comparisons between their results difficult, however it is clear that patient selection for lumbar surgery augmented with DIAM is a critical issue, which is not adequately defined in the literature. Investigations that improve the treatment algorithm and clinical guidelines associated with the use of the DIAM in lumbar surgery are warranted.

4.5 Conclusions: Phase I – Retrospective arm

L4/5 and L5/S1 were the most prevalent lumbar segments to be implanted with a DIAM as an augmentation of surgery for lumbar segment disease. Individuals had improved function (according to MCID recommendations) after 3 months, which was maintained to 24 months postoperatively. Pain improved to 6 months with gradual deterioration to 24 months despite remaining better compared to baseline. Cases with nerve root compression and facet joint pain syndrome showed a trend for deterioration beyond 3 months postoperatively. Patients with facet involvement reported greater improvement than those with disc involvement.

CHAPTER 5

Standing spinal curvature in asymptomatic healthy volunteers: a serial rasterstereographic assessment of sagittal lumbar curvature

5.1 Introduction

The intended application for 3D surface spinal curvature measurement systems has generally been the serial measurement of childhood scoliosis; therefore a limited literature reports normative sagittal lumbar curvature values employing these methods in adults (Bettany-Saltikov et al. 2002; Mannion et al. 2004; Lippold et al. 2006b; Crawford et al. 2009b). As outlined earlier in Chapter 2, studies have cautioned against the interchangeable use of measurements derived from different devices (Tillotson and Burton 1991; Norton et al. 2002). An exploration of available literature was therefore undertaken via Medline and CINAHL databases using the terms rasterstereography, spinal/lumbar standing curvature/posture. Known author and journal-based listings were also searched in order to reveal adult studies reporting standing lumbar curvature employing rasterstereography.

Two studies were identified; however the instrument had been applied to different samples with diverse assessment objectives thereby making comparisons between the two investigations difficult (Table 5.1). Crawford et al. (2009b) provided an initial report on lumbar lordosis (LL) after surgery with interspinous implant contrasted with ten healthy volunteers as controls. Lippold et al (2006a) report LL as a secondary finding to their results relating craniofacial morphology to thoracolumbar spinal shape. The Lippold et al study did not indicate the age range of subjects, however mean ages for both investigations suggest the Lippold et al (2006a) cohort were younger. Both studies pooled females and males.

Table 5.1: Summary of two studies using video rasterstereography to assess standing lumbar lordosis (LL) in adults without low back pain. The mean age and LL reported for each study were 11 years and close to 10˚ different, respectively, with comparable gender proportions.

Study	**Measurement Device**	**Subjects**					**LL**	
			Age			Gender		
		n	Mean	SD	Range		Mean	SD
Crawford et al, 2009	Video Rasterstereography	10	35.8	14.3	22-61	Male (4) Female (6)	46.0˚	11.7
Lippold et al, 2006	Video Rasterstereography	53	24.6	9	n/a	Male (21) Female (32)	36.5˚	9.1

n=subject number; SD=standard deviation; SLL=standing lumbar lordosis; n/a=not available

Given the gender distribution of subjects from both studies were comparable, their different mean LL (9.5 degrees) might be rationalised due to subject ages and/or each study's methodological emphasis (Lippold et al. 2006c; Crawford et al. 2009b).

An additional paper employing the ISIS measurement system in describing 3D back shape in 48 normal young adults, present their lumbar lordosis as a distance (mm) from a central axis (Bettany-Saltikov et al. 2002). This makes absolute comparisons with these two studies difficult.

Few investigations on surface spinal curvature report other than LL or thoracic kyphosis in healthy cases with a wide age range (Bullock-Saxton 1993; Youdas et al. 1996).The measurement and reference to sagittal balance as a spinal shape parameter is not generally applied to the assessment of surface curvature. It usually represents a feature in the evaluation of skeletal spinal alignment, about which there is an increasing literature (refer to Chapters 2.3 & 7.3). Investigations assessing spinal curvature from the skin surface generally limit the effects of postural sway and therefore any alteration to trunk inclination in standing is intentionally minimised (Youdas et al. 1995; Youdas et al. 2006). When employing images of the skin surface to derive spinal shape information (as in rasterstereography), quantifying trunk alignment with reference to the vertical is potentially important in appreciating shape characteristics. Rasterstereography affords this with the computation of trunk inclination, although the derived angle, like all other variables, only represents curvature at the instant the image is captured by the instrument. The angle of trunk inclination is known to vary in standing in both the anteroposterior (AP) and mediolateral (ML) planes, as a result of the economical and subtle sway that aims to balance the centre of mass over the feet (Lord et al. 1991a,b; Schwab et al. 2006). Aspects of postural sway were assessed as an adjunct to the main study, in order to elucidate potential physiological influences on curvature. These collateral investigations are included in Appendices VII.1-3 and will be specifically cross-referenced in the discussion of this chapter.

Various standing posture descriptors have been described and employed more recently in attempts to classify subjects with back pain for sub-group analysis (Kendall et al. 1993; Harris-Hayes et al. 2005; O'Sullivan 2005; Van Dillen et al. 2005). "Sway", "flat" and "hyperlordotic" postures are linked to back pain (O'Sullivan 2004,2005) and differ from the "ideal" posture characterised by normal ranges of thoracic and lumbar curvature and sagittal trunk alignment (Smith et al. 2008). Thus, what constitutes 'normal' thoracolumbar curvature is important but remains contentious. Smith et al (2008) characterise optimal posture by a lack of sagittal upper trunk displacement that coincides with lumbar and thoracic angulation within normal ranges. Normal ranges are however variable between and within populations (Christensen and Hartvigsen 2008).

The present study reports sagittal spinal curvature in 11 healthy volunteers who were measured at various time-points over two years, in order to provide a control group for posture comparisons to the surgery cohort. Literature reporting surface spinal curvature generally describes repeatability over short timeframes in healthy asymptomatic individuals, typically allowing for comparison with a different population of interest. Only one known study followed their healthy young female subjects for a two year period (Bullock-Saxton 1993). Given the dissimilarity of these subjects to the surgical cohort investigated in the present study, the need for an extended follow-up of a healthy cohort with a wide age range was identified. Curvature data obtained from a thermoplastic back phantom of fixed spinal shape measured over the same period are also reported to describe system accuracy. Lumbar lordosis (LL), thoracic kyphosis (TK), pelvic incidence (PI), and thoracolumbar sagittal balance (SB) derived by video rasterstereography were assessed.

This aspect of the investigation hypothesised that there would be variability of surface posture between healthy volunteers of a wide age range, however intra-individual serial change was expected to be minimal and not significant over two years. Based on the literature, it was anticipated that women would have a larger lumbar lordosis than men.

5.2 Methods

The study sample comprised 11 healthy volunteers [6 females, 5 males; aged 22-61 years; mean 34.6 (SD 14.1)] and a thermoplastic back phantom [based on a 14 year old girl with mild scoliosis (Goh et al. 1999b)]. The healthy subjects represented a convenience sample of volunteers who consented to serial follow-up spanning two years. They received no remuneration for their involvement. Thoracolumbar surface curvature was assessed in relaxed standing over the two-year course according to the testing protocol previously described in Chapter 3.6.4 for rasterstereography of healthy subjects. The thermoplastic back phantom was assessed at two time points that were two years apart.

Based on the derived dataset, descriptive statistics were used to present the variability in lumbar lordosis (LL), thoracic kyphosis (TK), pelvic incidence (PI) and sagittal balance (SB) as produced from rasterstereography within each five-trial session, and between time-points out to two years. These variables have been illustrated in Figure 3.x. Standard deviation and change scores represented intra- and inter-session curvature variability for the healthy subjects. Serial box-plots with outliers were employed to indicate the spread of group data, while line charts outlined the behaviour of individuals. Non-parametric paired comparisons were made between each time-point combination using Wilcoxon's signed rank test. Comparisons between nominal variables like gender or age, and continuous baseline variables were made using Mann-Whitney U tests. Relationships between variables were assessed with Spearman's rank correlation. A probability of $p<0.05$ was used as the criterion to represent meaningful differences.

5.3 Results

Mean (SD) results for lumbar lordosis (LL), thoracic kyphosis (TK), pelvic incidence (PI) and sagittal balance (SB) in 11 healthy volunteers and a thermoplastic phantom of fixed spinal curvatures are presented in Table 5.2. Box-plots depicting change over two years for LL, TK, PI and SB for 11 healthy volunteers are presented in Figure 5.1. Individual results for the same variables have been outlined in Figure 5.2.

Table 5.2: Mean sagittal spinal curvature results [mean (SD)] for 11 healthy volunteers and a single thermoplastic back phantom. Healthy subjects were imaged 5 times (and the data averaged) at each of 5 time-points over a 2 year period, while the thermoplastic phantom was imaged 5 times at each of two time-points, 2 years apart.

	Healthy Volunteers (n=11)					**Phantom**	
	Base	6w	6m	12m	24m	Base	24m
LL	45.6 (10.5)	46.4 (11.5)	46.6 (10.4)	44.6 (10.8)	46.2 (11.5)	26.4 (0.2)	26.3 (0.1)
TK	58.4 (14.5)	58.4 (15.4)	58.2 (15.5)	55.5 (12.1)	56.9 (13.6)	29.0 (0.2)	28.9 (0.2)
PI	21.4 (6.2)	22.8 (6.1)	22.6 (6.3)	21.5 (6.1)	22.0 (6.5)	16.8 (0.1)	16.7 (0.3)
SB	26.6 (24.5)	30.2 (22.7)	21.0 (27.8)	23.5 (24.5)	27.3 (24.2)	10.5 (0.4)	10.4 (0.4)

Base=baseline; 6w=6 weeks; 6-24m=monthly time-point; LL=lumbar lordosis (˚); TK=thoracic kyphosis (˚); PI=pelvic incidence (˚); SB=sagittal balance (mm) as measured via rasterstereography in standing.

5.3.1 Serial change, gender and age differences:

System precision examined by repeated images of the thermoplastic back phantom showed high reproducibility with no significant change in surface curvature over two years. No significant differences in lumbar lordosis or thoracic kyphosis occurred at any time-point compared to baseline values for the 11 healthy cases. Subtle increases ($p<0.001$) to pelvic incidence occurred at 6 weeks (22.8˚) and 6 months (22.6˚) compared to baseline (21.4˚) but were equivalent again at one and two years. Sagittal balance was more positive at 6 weeks (30.2mm) and more negative at 6 months (21.0mm) compared to baseline values (26.6mm); however it was no different a year and two years after initial assessment ($p<0.001$).

Individual data and changes compared to baseline for LL, TK, PI and SB are presented in Tables 5.2-5, respectively.

Baseline results for each variable when analysed according to gender showed significantly more lumbar lordosis, pelvic incidence and sagittal balance in the 6 female cases compared to the 5 males ($p<0.0001$).

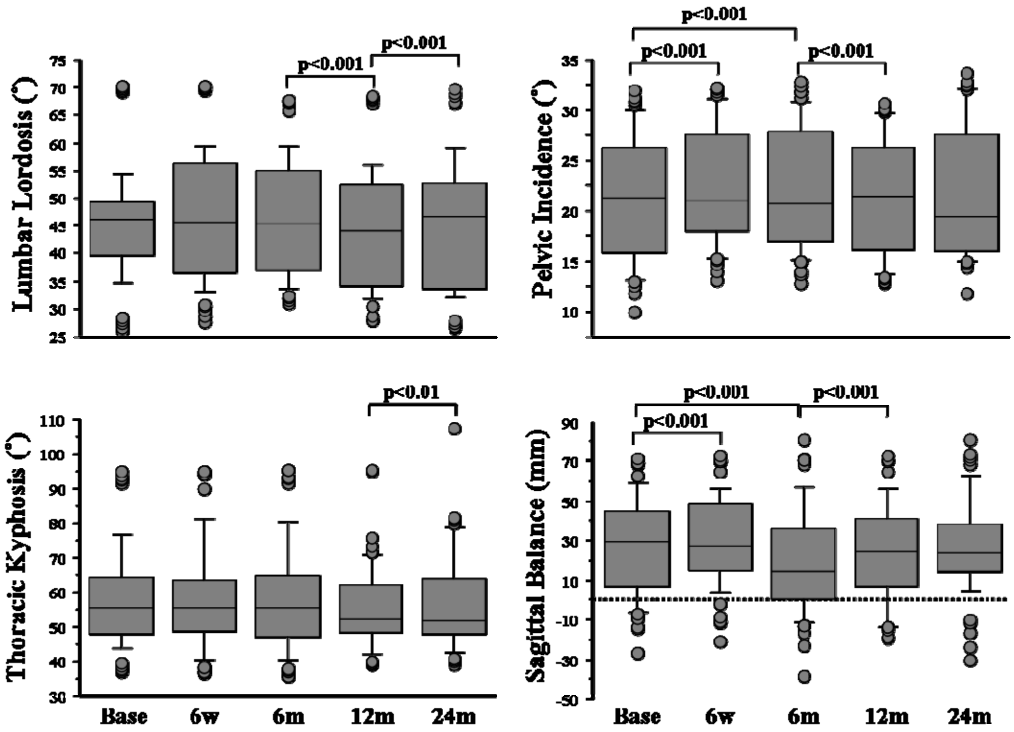


Figure 5.1: Box-plots revealing spinal curvature change ($p<0.05$) over two years in 11 healthy volunteers measured via rasterstereography for lumbar lordosis, thoracic kyphosis, pelvic incidence and sagittal balance. Outliers have been included to indicate true data spread. No measure was significantly different compared to baseline at either 12 or 24 months later.

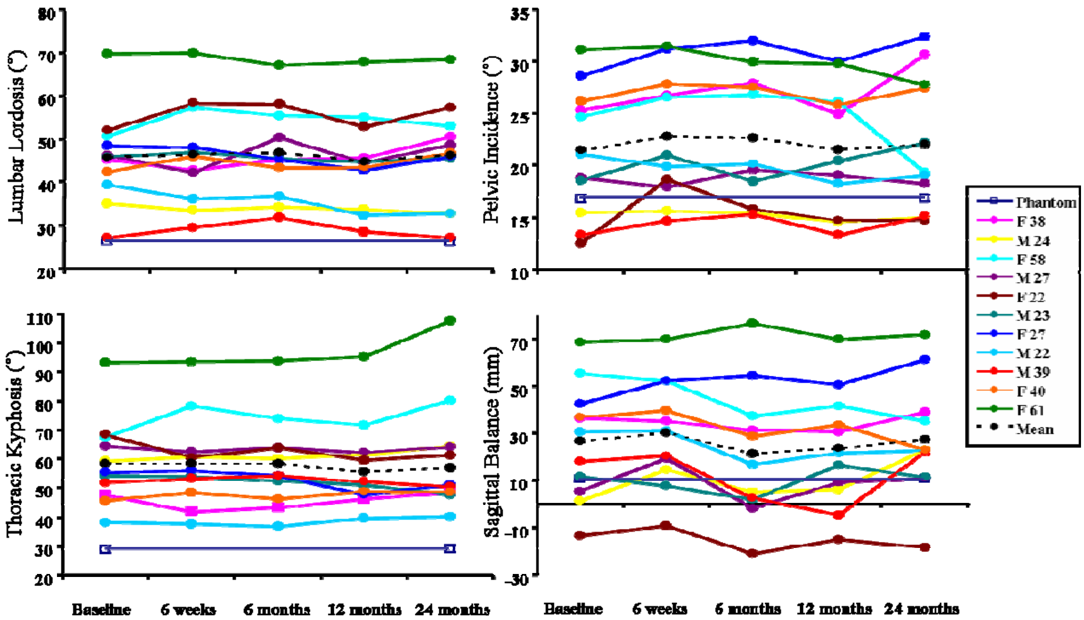


Figure 5.2: Individual mean time-point values for lumbar lordosis, thoracic kyphosis, pelvic incidence and sagittal balance in 11 healthy volunteers and a single thermoplastic back phantom over a two-year period. The figure key indicates the gender (F=female; M=male) and age of each individual. The cohort mean is presented with a dotted black line.

There was no difference in thoracic kyphosis between genders. Table 5.6 presents the mean results according to gender, while Figure 5.3 provides box-plots demonstrating the data spread and significant differences between the genders' baseline values.

At baseline, female lumbar lordosis ranged from 42.3° to 69.8° (mean 51.4, SD 9.1) while the 5 males ranged from 27.3° to 46.0° (mean 38.6, SD 9.1). Thoracic kyphosis ranged from 45.6° to 93.2° for the women (mean 62.6, SD 16.9) and from 38.2° to 64.3° in males (mean 53.5, SD 9.1). Female pelvic incidence ranged between 12.5° to 31.1° (mean 24.7, SD 6.4) while men ranged between 13.3° and 21.0° (mean 17.4, SD 3.0). Sagittal balance in the women ranged from -13.6mm and 68.7mm (mean 37.7, SD 26.6) and in the men from 1.1mm to 30.5mm (mean 13.2, SD 12.3). No difference was noted between genders when change in LL, TK and PI at each time-point compared to baseline was assessed. The reductions in sagittal balance at 12 months compared to baseline for females (-2.6mm) and males (-3.7mm) were significantly different ($p<0.05$).

Baseline results for each variable when analysed according to dichotomised age (≤35yrs<) showed no differences in LL or TK. Those aged over 35yrs had significantly greater PI [24.1 (6.1) vs 19.2 (5.2); $p<0.05$)] and a more positive SB [43.0 (18.8) vs 12.9 (20.0); $p<0.05$)] than the younger subjects at baseline. Table 5.7 presents the mean results according to age, while Figure 5.4 provides box-plots demonstrating the data spread and significant differences between baseline values for both age groups.

At baseline, lumbar lordosis ranged from 34.6° to 53.5° in the 6 cases younger than 35yrs (mean 44.4, SD 6.0) while the 5 older volunteers ranged from 26.1° to 70.3° (mean 47.0, SD 14.1). Thoracic kyphosis ranged from 37.2° to 71.0° for those ≤35yrs (mean 56.1, SD 9.8) and from 44.2° to 94.9° in the >35yrs subjects (mean 61.1, SD 18.3). Pelvic incidence in the ≤35yrs cases ranged between 10.0° to 29.8° (mean 19.2, SD 5.2) while >35yrs ranged between 12.9° and 32.0° (mean 24.1, SD 6.1).

Sagittal balance in those ≤35yrs ranged from -26.5mm and 46.4mm (mean 12.9, SD 20.0) and in the over 35s from 13.3mm to 72.1mm (mean 43.0, SD 18.8). No difference was noted between age groups when changes in any of the four variables at each time-point were assessed compared to baseline.

Table 5.3: Repeatability of assessing lumbar lordosis (LL) as measured by rasterstereography for 11 healthy subjects (n1-11) and a single thermoplastic back phantom (Ph). Subjects were imaged in standing 5 times on each of 5 occasions over a 2 year period. Results for baseline, 6 weeks, 6, 12 and 24-months are presented. Changes in surface LL between time-points for each subject are represented as change scores (△) where a negative value indicates flattening of the lumbar curvature.

n	F/M Age	Baseline (B)	6 weeks	△6w-B	6 months	△6m-B	12 months	△12m-B	24 months	△24m-B
Ph	F14	26.4 (0.2) [0.1][1]							26.3 (0.1) [0.5]	-0.1[3]
1	F22	52.1 (1.5) [2.9]	58.2 (1.3) [2.2]	6.1	58.1 (1.8) [3.2]	6.0	52.7 (0.7) [1.4]	0.6	57.2 (2.7) [4.7]	5.1
2	F27	48.3 (1.2) [2.6]	47.9 (0.2) [1.5]	-0.4	45.1 (0.3) [0.7]	-3.2	42.6 (0.7) [1.6]	-5.7	45.7 (0.7) [1.6]	-2.6
3	F38	45.1 (1.6) [3.6]	42.8 (1.1) [2.5]	-2.3	45.3 (0.4) [0.8]	0.2	45.6 (0.5) [1.1]	0.5	50.5 (0.8) [1.5]	4.6
4	F40	42.3 (0.8) [1.8]	45.9 (1.1) [2.3]	3.6	43.2 (0.7) [1.7]	0.9	43.4 (0.6) [1.3]	1.1	46.7 (0.6) [1.2]	4.4
5	F58	50.7 (2.7) [10.0]	57.3 (0.8) [1.4]	6.6	55.5 (1.4) [2.4]	4.8	55.0 (0.9) [1.6]	4.3	52.9 (0.5) [0.9]	2.2
6	F61	69.8 (0.4) [0.6]	70.0 (0.2) [0.3]	0.2	67.2 (0.8) [1.1]	-2.6	67.9 (0.6) [0.8]	-1.9	68.4 (1.1) [1.5]	-1.4
7	M22	39.3 (0.4) [0.9]	36.0 (0.5) [1.5]	-3.3	36.7 (0.5) [1.4]	-2.6	32.2 (0.3) [0.9]	-7.1	32.7 (1.8) [1.8]	-6.6
8	M23	45.7 (3.4) [10.0]	46.9 (1.4) [2.9]	1.2	45.4 (2.2) [4.9]	-0.3	44.7 (0.8) [1.7]	-1.0	45.6 (0.5) [1.1]	-0.1
9	M24	34.9 (0.5) [1.4]	33.5 (0.3) [1.0]	-1.4	34.1 (0.6) [1.7]	-0.8	33.6 (0.5) [1.4]	-1.3	32.7 (0.6) [1.8]	-2.2
10	M27	46.0 (1.2) [2.5]	42.1 (1.9) [4.6]	-3.9	50.4 (3.6) [10.0]	4.4	44.4 (0.8) [1.8]	-1.6	48.6 (1.7) [3.4]	2.6
11	M39	27.3 (0.9) [3.4]	29.5 (1.3) [4.4]	2.2	31.8 (0.4) [1.4]	4.5	28.5 (1.2) [4.1]	1.2	27.1 (0.5) [1.9]	-0.2
34.6 (14.1)		45.6 (1.3) [3.6][2]	46.4 (0.9) [2.2]	0.8 (3.6)[3]	46.6 (1.2) [2.7]	1.0 (3.4)[3]	44.6 (0.7) [1.6]	-1.0 (3.2)[3]	46.1 (1.0) [1.9]	0.5 (3.6)[3]

B=baseline; 6, 12, 24m=monthly time-point; △=change score; Ph=thermoplastic back phantom.
1 Five-trial measurements for each subject; mean (SD) [CV%]
2 All 11 subjects; mean (average SD) [average CV%]
3 NS=notsignificant

Table 5.4: Repeatability of assessing thoracic kyphosis (TK) as measured by rasterstereography for 11 healthy subjects (n1-11) and a single thermoplastic back phantom (Ph). Subjects were imaged in standing 5 times on each of 5 occasions over a 2 year period. Results for baseline, 6 weeks, 6, 12 and 24-months are presented. Changes to surface LL between time-points for each subject are represented as change scores (△) where a negative value indicates flattening of the lumbar curvature.

n	F/M Age	Baseline (B)	6 weeks	△6w-B	6 months	△6m-B	12 months	△12m-B	24 months	△24m-B
Ph	F14	29.0 (0.2) [0.7][1]							28.9 (0.2) [0.8]	-0.1[3]
1	F22	68.2 (4.9) [10.0]	60.3 (3.1) [5.1]	-7.9	63.7 (2.4) [6.9]	-4.5	59.4 (3.5) [5.9]	-8.8	61.2 (2.1) [3.4]	-7.0
2	F27	55.1 (0.8) [1.4]	55.8 (1.1) [2.0]	0.7	54.2 (1.3) [2.5]	-0.9	47.6 (0.9) [1.9]	-7.5	51.0 (2.2) [3.7]	-4.1
3	F38	47.6 (1.5) [3.1]	42.0 (1.5) [3.5]	-5.6	43.2 (1.3) [3.0]	-4.4	46.2 (2.2) [4.8]	-1.4	48.5 (0.6) [1.1]	0.9
4	F40	45.6 (1.1) [2.4]	48.4 (1.2) [2.4]	2.8	46.2 (2.0) [4.4]	0.6	48.7 (0.8) [1.6]	3.1	48.4 (2.4) [4.9]	2.8
5	F58	67.3 (6.3) [10.0]	78.1 (1.0) [1.2]	10.8	73.9 (2.3) [3.1]	6.6	71.6 (3.5) [4.9]	4.3	80.2 (1.8) [2.2]	12.9
6	F61	93.2 (1.2) [1.3]	93.6 (2.1) [2.2]	0.4	93.7 (1.7) [1.8]	0.5	95.1 (0.4) [0.4]	1.9	107.7	14.5
7	M22	38.2 (1.0) [2.5]	37.5 (0.8) [2.2]	-0.7	36.8 (1.0) [2.6]	-1.4	39.6 (0.4) [1.0]	1.4	40.2 (0.6) [4.3]	2.0
8	M23	54.1 (1.0) [1.8]	53.8 (1.3) [5.1]	-0.3	52.4 (1.3) [2.5]	-1.7	51.0 (2.1) [4.1]	-3.1	47.6 (1.8) [3.4]	-6.5
9	M24	59.2 (1.1) [1.9]	60.5 (1.6) [2.6]	1.3	60.1 (2.2) [3.7]	0.3	61.4 (1.5) [2.4]	2.2	64.3 (2.7) [4.2]	5.1
10	M27	64.3 (2.2) [3.5]	62.4 (3.6) [5.8]	-1.9	63.7 (4.4) [6.9]	-0.6	62.0 (2.3) [3.8]	-2.3	64.0 (1.1) [1.7]	-0.3
11	M39	51.8 (0.5) [1.0]	53.3 (2.4) [2.4]	1.5	53.9 (3.4) [6.3]	2.1	52.0 (0.6) [1.1]	0.2	50.3 (1.5) [3.0]	-1.5
34.6 (14.1)		58.6 (2.0) [3.5][2]	58.7 (1.8) [3.1]	0.1 (4.8)[3]	58.3 (2.1) [4.0]	-0.3 (3.1)[3]	57.7 (1.7) [2.9]	-0.9 (4.2)[3]	60.3 (1.7) [3.2]	1.7 (7.0)[3]

B=baseline; 6, 12, 24m=monthly time-point; △=change score; Ph=thermoplastic back phantom.
[1] Five-trial measurements for each subject; mean (SD) [CV%]
[2] All 11 subjects; mean (average SD) [average CV%]; [3] NS=not significant

Table 5.5: Repeatability of assessing pelvic incidence (PI) as measured by rasterstereography for 11 healthy subjects (n1-11) and a single thermoplastic back phantom (Ph). Subjects were imaged in standing 5 times on each of 5 occasions over a 2 year period. Results for baseline, 6 weeks, 6, 12 and 24-months are presented. Changes to surface LL between time-points for each subject are represented as change scores (△) where a negative value indicates flattening of the lumbar curvature.

n	F/M Age	Baseline (B)	6 weeks	△6w-B	6 months	△6m-B	12 months	△12m-B	24 months	△24m-B
Ph	F14	16.8 (0.1) [1]							16.7 (0.3) [2]	-0.1[3]
1	F22	12.5 (1.8) [10.0]	18.6 (1.3) [7.0]	6.1	15.8 (1.7) [11.0]	3.3	14.7 (1.6) [10.6]	2.2	14.7 (1.8) [12.0]	2.2
2	F27	28.6 (1.0) [3.4]	31.2 (1.0) [3.0]	2.6	32.0 (1.7) [8.0]	3.4	30.0 (0.5) [1.5]	1.4	32.4 (0.4) [1.0]	3.8
3	F38	25.3 (0.5) [2.1]	28.2 (3.8) [13.0]	2.9	27.9 (0.3) [1.0]	2.6	24.9 (1.8) [7.4]	-0.4	30.7 (2.3) [7.0]	5.4
4	F40	26.2 (0.5) [1.8]	27.9 (0.8) [3.0]	1.7	27.5 (1.1) [4.0]	1.3	25.9 (0.8) [3.3]	-0.3	27.4 (0.2) [1.0]	1.2
5	F58	24.7 (3.1) [10.0]	26.6 (1.0) [4.0]	1.9	26.8 (0.6) [2.0]	2.1	26.1 (1.3) [5.2]	-1.4	19.3 (0.4) [2.0]	-5.4
6	F61	31.1 (0.6) [1.8]	31.4 (0.7) [2.0]	0.3	30.0 (0.8) [3.0]	-0.9	29.8 (0.1) [0.5]	-1.3	27.7 (1.2) [4.0]	-3.4
7	M22	21.0 (0.5) [2.3]	19.8 (0.6) [3.0]	-1.2	20.1 (1.7) [8.0]	-0.9	18.2 (0.7) [3.7]	-2.8	19.0 (0.4) [2.0]	-2.0
8	M23	18.5 (1.7) [10.0]	21.0 (1.0) [5.0]	2.5	18.4 (1.4) [8.0]	-0.1	20.4 (1.8) [8.8]	1.9	22.2 (1.2) [5.0]	3.7
9	M24	15.5 (1.0) [10.0]	15.6 (0.8) [5.0]	0.1	15.3 (1.1) [7.0]	-0.2	14.6 (1.0) [5.1]	-0.9	15.0 (0.5) [3.0]	-0.5
10	M27	18.7 (1.1) [10.0]	17.9 (1.5) [8.0]	-0.8	19.6 (1.3) [7.0]	0.9	19.0 (0.9) [4.5]	-0.3	18.2 (0.6) [3.0]	-0.5
11	M39	13.3 (0.6) [4.3]	14.6 (1.2) [8.0]	1.3	15.3 (1.0) [7.0]	2.0	13.3 (0.7) [5.4]	0	15.0 (0.2) 1.0]	1.7
34.6 (14.1)		21.4 (1.1) [6.0][2]	22.6 (1.2) [5.5]	1.6 (2.0)[4]	22.6 (1.2) [6.0]	1.2 (1.6)[4]	21.5 (0.9) [5.1]	-0.2 (1.5)[3]	22.0 (0.8) [3.7]	0.6 (3.3)[3]

B=baseline; 6, 12, 24m=monthly time-point; △=change score; Ph=thermoplastic back phantom.
[1] Five-trial measurements for each subject; mean (SD) [CV%]
[2] All 11 subjects; mean (average SD) [average CV%]; [3] NS=not significant; [4] $p<0.001$

Table 5.6: Repeatability of assessing thoracolumbar sagittal balance (SB) as measured by rasterstereography for 11 healthy subjects (n1-11) and a single thermoplastic back phantom (Ph). Subjects were imaged in standing 5 times on each of 5 occasions over a 2 year period. Results for baseline, 6, 12 and 24-months are presented. Changes to surface LL between time-points for each subject are represented as change scores (△) where a negative value indicates flattening of the lumbar curvature.

n	**F/M Age**	**Baseline (B)**	**6 weeks**	**△6w-B**	**6 months**	**△6m-B**	**12 months**	**△12m-B**	**24 months**	**△24m-B**
Ph	F14	10.6 (0.4) [4]							10.4 (0.4) [4]	-0.2[3]
1	F22	-13.6 (8.0) [59]	-9.2 (9.1) [99]	4.4	-20.8 (10.8) [52]	-7.2	-15.1 (2.4) [16]	-1.5	-18.2 (8.6) [47]	-4.6
2	F27	42.6 (3.0) [7]	52.1 (2.7) [5]	9.5	54.6 (1.9) [4]	12.0	50.6 (4.8) [10]	8.0	61.2 (6.3) [10]	18.6
3	F38	36.4 (8.2) [23]	35.1 (5.8) [16]	-1.3	31.1 (2.1) [7]	-5.3	30.4 (5.6) [18]	-6.0	38.8 (8.2) [21]	2.4
4	F40	36.5 (7.7) [33]	39.6 (9.5) [47]	3.1	28.7 (7.0) [24]	-7.8	33.3 (7.2) [22]	-3.2	22.9 (4.9) [21]	-13.6
5	F58	55.5 (3.6) [6]	52.3 (3.7) [7]	-3.2	37.4 (4.9) [13]	-18.1	41.6 (3.7) [9]	-13.9	35.2 (5.4) [15]	-20.3
6	F61	68.7 (3.3) [21]	70.0 (2.9) [4]	1.3	76.7 (9.0) [12]	8.0	70.0 (2.9) [4]	1.3	71.9 (6.7) [9]	3.2
7	M22	30.5 (1.5) [5]	30.8 (5.2) [17]	0.3	16.5 (10.1) [61]	-14.0	21.5 (3.4) [164]	-9.0	22.3 (5.9) [26]	-8.2
8	M23	11.4 (13.2) [116]	7.6 (7.3) [96]	-3.8	1.8 (7.0) [391]	-9.6	16.1 (7.2) [45]	4.7	11.1 (3.1) [28]	-0.3
9	M24	1.1 (3.6) [318]	14.3 (5.1) [36]	13.2	5.0 (6.7) [135]	3.9	5.9 (4.7) [79]	4.8	22.8 (2.9) [13]	21.7
10	M27	5.4 (4.6) [86]	19.1 (1.9) [10]	13.7	-2.0 (5.6) [286]	-7.4	8.8 (2.7) [30]	3.4	10.8 (3.7) [34]	5.4
11	M39	17.8 (5.9) [33]	20.1 (9.5) [47]	2.3	2.3 (5.9) [257]	-15.5	-4.7 (7.8) [164]	-22.5	21.8 (5.2) [24]	4.0
34.6 (14.1)		26.6 (5.7) [64][2]	30.2 (5.7) [34]	3.6 (5.1)[4]	21.0 (6.5) [113]	-5.5 (9.7)[4]	23.5 (4.8) [51]	-3.1 (9.2)[3]	27.0 (5.5) [22]	0.8 (12.5)[3]

B=baseline; 6, 12, 24m=monthly time-point; △=change score; Ph=thermoplastic back phantom.
[1] Five-trial measurements for each subject; mean (SD) [CV%]
[2] All 11 subjects; mean (average SD) [average CV%]
[3] NS=not significant [4] $p<0.001$

Table 5.7: Mean sagittal spinal curvature results [mean (SD)] for 6 female and 5 male healthy volunteers. Subjects were imaged 5 times at each of 5 time-points over a 2-year period.

	Baseline		**6 weeks**		**6 months**		**12 months**		**24 months**		Δ
	F	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	
LL	51.4	38.6	53.7	37.6	52.4	39.7	51.2	36.7	53.6	37.3	NS
	(9.1)	(9.1)	(9.4)	(6.4)	(8.9)	(7.4)	(8.9)	(6.8)	(7.9)	(8.5)	
TK	62.6	53.5	62.5	53.5	62.5	52.6	57.7	53.2	60.2	53.4	NS
	(16.9)	(9.1)	(18.2)	(9.4)	(17.8)	(9.8)	(14.5)	(8.5)	(15.8)	(10.0)	
PI	24.7	17.4	27.1	17.8	26.7	17.7	25.2	17.1	25.4	17.9	NS
	(6.4)	(3.0)	(6.1)	(2.7)	(5.7)	(2.3)	(5.6)	(3.0)	(6.9)	(3.0)	
SB	37.7	13.2	40.0	18.4	34.6	4.7	35.1	9.5	35.3	17.8	12m
	(26.6)	(12.3)	(25.7)	(9.7)	(30.9)	(9.2)	(26.7)	(10.5)	(30.1)	(6.9)	$p<0.05$

Mean (SD); F=females; M=males; Δ=differences between genders for serial changes compared to baseline; LL=lumbar lordosis; TK=thoracic kyphosis; PI=pelvic incidence; SB=sagittal balance; NS=no significant difference

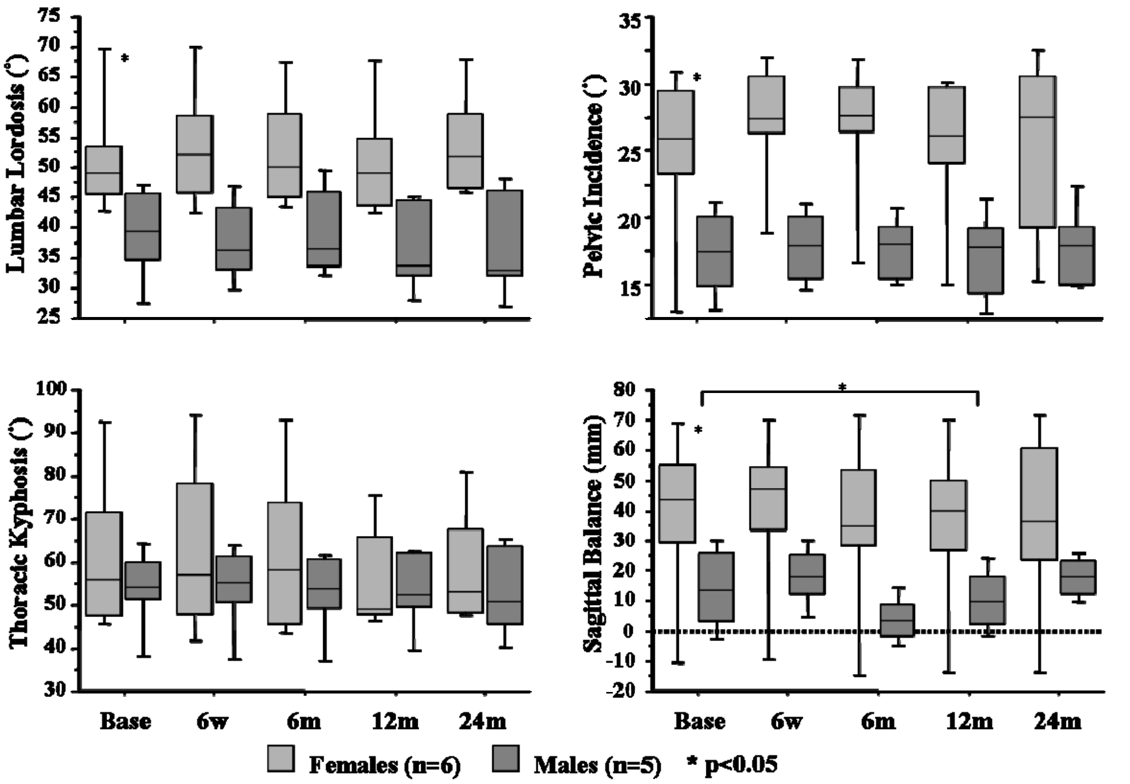


Figure 5.3: Box-plots indicating the behaviour according to gender of four aspects of sagittal curvature over a two-year period as measured via rasterstereography in 11 healthy volunteers. Significant (*p<0.05) differences between genders for each set of baseline values plus changes compared to baseline are indicated. Refer also to Table 5.6.

Table 5.8: Mean sagittal spinal curvature results [mean (SD)] for 6 healthy volunteers ≤35 years of age and 5 older than 35yrs. Subjects were imaged 5 times each at 5 time-points over a 2 year period.

	Baseline		**6 weeks**		**6 months**		**12 months**		**24 months**		**Δ**
	<35	**>35**	**<35**	**>35**	**<35**	**>35**	**<35**	**>35**	**<35**	**>35**	
LL	44.4	47.0	44.1	49.1	45.0	48.6	41.7	48.1	43.7	49.1	NS
	(6.0)	(14.1)	(8.4)	(14.1)	(8.4)	(12.2)	(7.1)	(13.3)	(9.0)	(13.5)	
TK	56.1	61.1	55.1	62.5	54.7	62.2	53.5	58.3	54.7	60.3	NS
	(9.8)	(18.3)	(8.9)	(20.2)	(9.8)	(19.6)	(8.5)	(15.5)	(9.4)	(8.1)	
PI	19.2	24.1[1]	20.7	25.4	20.9	25.5	19.5	24.0	20.3	24.0	NS
	(5.2)	(6.1)	(5.2)	(5.9)	(5.8)	(5.4)	(5.4)	(5.8)	(6.1)	(6.1)	
SB	12.9	43.0[1]	19.1	43.4	9.2	35.2	14.6	34.1	18.3	38.1	NS
	(20.0)	(18.8)	(20.1)	(18.3)	(24.5)	(25.1)	(20.5)	(25.0)	(24.4)	(19.4)	

Mean (SD); <35=less than 35yrs; >35=35 years or more; Δ=differences between age groups for serial change compared to baseline; LL=lumbar lordosis; TK=thoracic kyphosis; PI=pelvic incidence; SB=sagittal balance; NS=no significant difference; [1]Significant difference of mean baseline values between subjects older or younger than 35yrs ($p<0.05$).

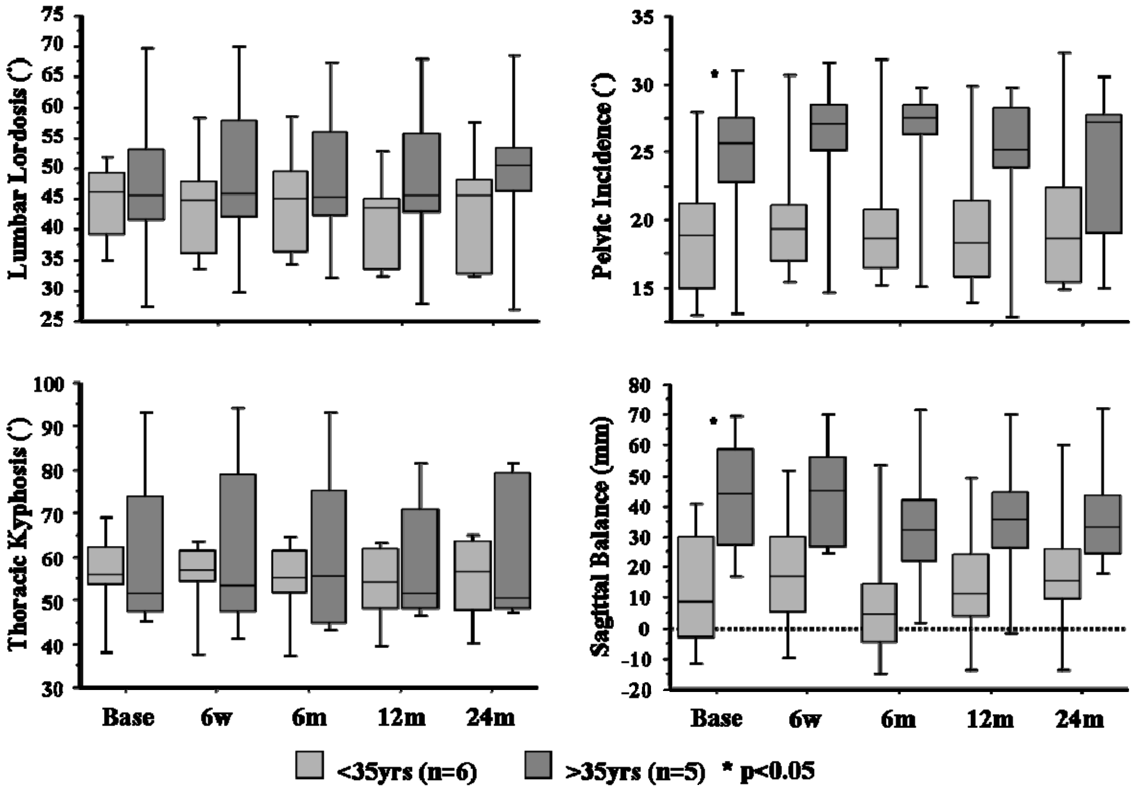


Figure 5.4: Box-plots indicating the behaviour according to age of four aspects of sagittal curvature over a two-year period as measured via rasterstereography in 11 healthy volunteers. Significant (*$p<0.05$) differences between the two age groups for each set of baseline values are indicated. Refer to Table 5.7.

5.3.2 Relationships between variables

Correlations between variables at baseline showed: a strong direct relationship between pelvic incidence and sagittal balance ($\rho=0.88$; $p<0.01$) and a moderate relationship between lumbar lordosis and thoracic kyphosis ($\rho=0.76$; $p=0.01$). No significant relationship existed between:

lumbar lordosis and both pelvic incidence (ρ=0.40; NS); and sagittal balance (ρ = 0.33; NS); thoracic kyphosis and each of pelvic incidence (ρ=-0.05; NS); and sagittal balance (ρ=0.00; NS). These comparisons have been graphically presented in Figure 5.5.

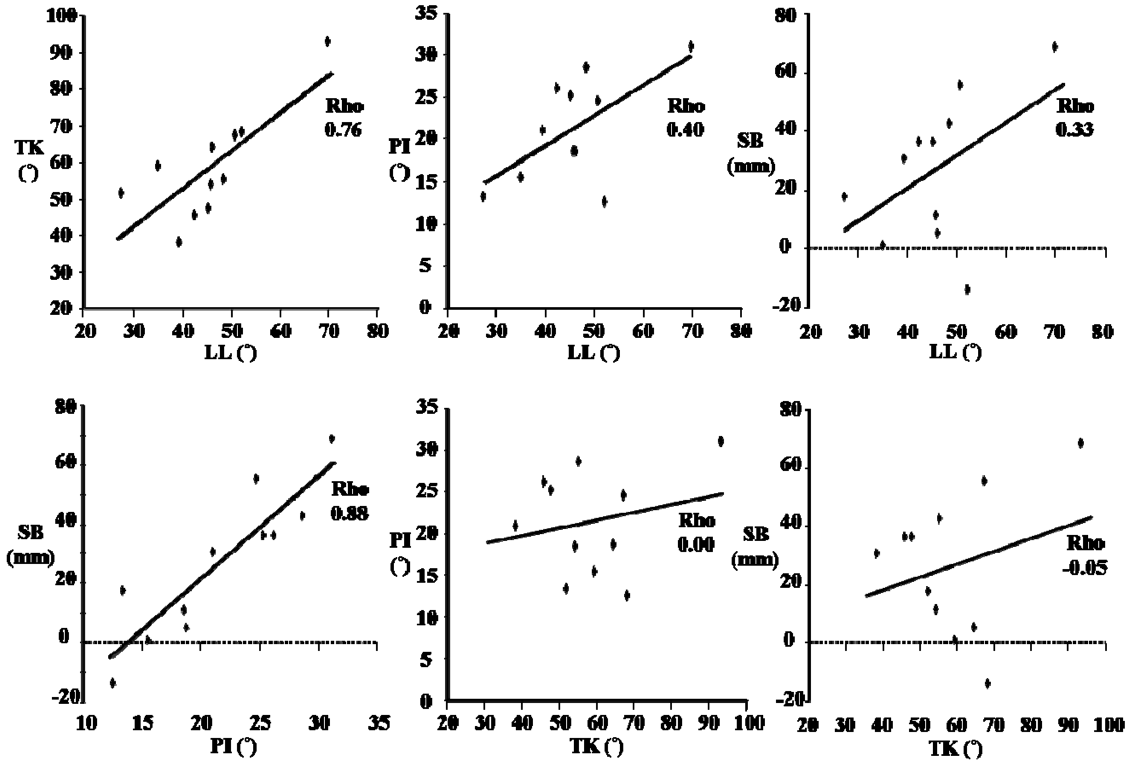


Figure 5.5: Scatter graphs outlining the relationships between group data for the variables lumbar lordosis (LL), thoracic kyphosis (TK), pelvic incidence (PI) and sagittal balance (SB)

5.4 Discussion

5.4.1 Serial change, gender and age differences: This study has demonstrated that within a session and at one and two years later, a healthy asymptomatic person’s spinal curvature is consistent when asked to stand comfortably erect. Lumbar lordosis and thoracic kyphosis do not change appreciably throughout the full two-year course, while pelvic incidence and sagittal balance have the potential for variability. Based on these findings, it would appear that an individual’s postural awareness is sufficiently consistent to afford repeatable standing. Any deviations within the course of at least two years are therefore not likely to be as a result of chance and potentially relate to extrinsic factors, which might include back pain and associated treatment interventions. These aspects of the findings from the present study are in agreement with another study that investigated thoracolumbar posture over an extended time frame. Bullock-Saxton (1993) assessed 13 healthy asymptomatic women aged 18-19 years for 24 months, and although not supported by curvature data, showed differences in pelvic tilt within the middle 16 months of the two year follow-up. Thoracolumbar posture in the short (4-8 days) and longer (24 months) terms remained unchanged (Bullock-Saxton 1993). The present study provides confirmation that a repeatable posture in healthy asymptomatic people is true for both genders of a wide age range. It can be assumed that the consistent thoracic and lumbar curvature over two years applies to people with back pain, symptomatic or not. Whether posture as measured from the skin surface is affected by lumbar surgical interventions and namely interspinous implant will be discussed later in Chapter 7.2.

The finding that pelvic incidence and sagittal balance were demonstrably variable within two years attracts speculation regarding common physiological influences between the two. Both parameters are derived with rasterstereography by referencing the vertical (Figure 3.3) and are therefore subject to changes in trunk inclination. Postural sway is a key requirement in efficient standing wherein an individual will move within a conical-shaped region, centred at the feet, in order to maintain their centre of mass over its base of support (Lord et al. 1991b; Schwab et al. 2006). This subtle multidirectional motion, mediated by minimal muscular effort, includes relative movement in the anteroposterior (AP) and mediolateral planes, which alters the pitch of the trunk in relation to the vertical (Ortengren and Andersson 1977; Lord et al. 1991b,a). Measurements of pelvic incidence and spinal alignment and balance are reported as sagittal curvature parameters and as such reference the AP plane in their derivation. The potential for normal physiological sway to impact on the measurement of PI and SB using rasterstereography, which provides data based on a single moment within the sway excursion only, is noted. The extent of motion as a consequence of postural sway has been further explored in Appendices VII.1&2, the results of which indicate that AP motion in quiet standing predominates.

Closer inspection of Tables 5.3-5.6 indicates higher intra-subject variability for SB (CV: 22-113%) compared to the ranges noted for PI (CV: 3.3-6.1%), TK (CV: 2.9-4.0%) and LL (CV: 1.6-3.6%). It may be speculated that the strongest influence that postural sway has on a parameter obtained from rasterstereography, in the sagittal profile at least, would be on the angle of trunk inclination as the body subtly moves to maintain their cone of economy (Schwab et al. 2006). Therefore sagittal balance, as derived using the method described in this study, would represent the most influenced variable measured in this investigation.

Lumbar lordosis: Results for the present study report an initial mean (SD) LL of 45.6˚ (SD 10.5˚) for healthy volunteers of a wide age range, and when compared to baseline, this did not vary over the two-year period of observation. This value appears somewhat high when contrasted to results of the pooled studies presented in Tables 2.8 and 5.1. These other studies report mean LL ranging between 23.0˚ and 36.5˚, so the highest group values reported for SLL in the literature are 10˚ less than the present findings. Differences in the reported lumbar angles may be related to various aspects including the assessment instruments and methods employed such as the tangent or trigonometric methods, the end-point reference vertebrae or surface landmarks, and the use of digital interfaces. In addition, the known influence of gender and potential contribution of other factors like age and comorbidities should be considered with any results and comparisons applied with caution. The influence of arm position in LL in standing (Appendix VII.2) should not have implicated on these healthy volunteers who stood with their arms by the side for this series of tests.

The small group of healthy volunteers spanning a wide age range used in this serial study revealed 12.8˚ greater mean lumbar lordosis in females (51.4˚ ± 9.1˚) than males (38.6˚ ± 9.1˚). This difference in LL between genders is in agreement with previous investigations (Youdas et al. 1996; Norton et al. 2004; Youdas et al. 2006) although reported mean values between each study differ. Variation in values of SLL between investigators may be explained by diversity of instruments used and/or the study emphasis (Tillotson and Burton 1991; Norton et al. 2002). Youdas et al (1996) reported similar values to the present study for their female (52.7˚ ± 15.3˚) and male (37.5˚ ± 11.0˚) cases aged between 40-69 years, having used a flexible curve via the tangent method. Similarly, in using the Metrecom electrogoniometer, Norton et al (2004) reported the average female SLL to be 45.6˚ (± 15.3˚), while the male mean was 33.7˚ (± 11.5˚). In a later study employing the flexicurve, Youdas et al (2006) reported the mean SLL difference between genders to be narrower at 6.5˚, which represents half the difference noted in the present study. Despite these described differences between studies employing varied measurement instruments, all values reported between studies lie within one standard deviation of each other.

The present study found no difference in mean LL between subjects older or younger than 35 years. Similarly, Singh et al (2010) reported no difference in LL between their two groups of healthy subjects who were either <35yrs or >65yrs and who were measured using an electromagnetic tracking device applied to the midline skin overlying the spinous processes (Singh et al. 2010). Milne and Lauder (1974) showed an increasingly large proportion of both genders over 60 years of age with an absent LL as measured by flexicurve. Given the present study includes evaluation of only one case aged over 60 years, it might be argued that, in relation to LL at least, the current cohort was too young for any age differences to be detected.

Thoracic kyphosis: Results [mean (± 1SD; range)] for the present study report an initial mean TK of 58.4˚ (± 14.5˚; 38.2˚ to 93.2˚) for healthy volunteers of a wide age range, which did not vary over the two year period of observation. No differences in TK between genders or age groups were noted. These results are in agreement with Korovessis et al (2002) who found no differences in surface TK relating to gender or age in their series of adolescents measured with the Debrunner kyphometer. The mean TK in their series was 44.7˚ (SD 2.7˚, range 27 to 62˚). The difference in group mean between the two studies potentially relates to the age groups studied where the present cohort included a proportion of subjects (4 of 11) aged in their 5th to 7th decades, while Korovessis et al (2002) only studied those in their 2nd or 3rd decade.

Age-related progression of thoracic kyphosis is a well-defined process that is influenced by the morphology of the vertebral bodies and intervertebral discs (Goh et al. 1999c). O'Gorman & Jull (1987) have shown that surface thoracic kyphosis as measured via an inclinometer, increases significantly with age beyond 50 years (O'Gorman and Jull 1987). Similarly, another earlier paper employing flexicurve found an increased kyphosis in women over 50 and men over 60 years (Milne and Lauder 1974). A recent study employing an electromagnetic tracking device to assess surface spinal curvature in adults (younger than 35 years or older than 65 years) showed 8˚ more kyphosis in older cases (Singh et al. 2010). Despite evidence that age-related increases in TK are more marked in women that men (Fon et al. 1980), Milne and Williamson (1983) reported this was not true over a 5 year longitudinal follow-up when assessed from the surface using a flexicurve (Milne and Williamson 1983). The results of the present study appear to be in agreement with these earlier investigations despite their being no significant increase in TK noted over the two-year period of observation. Although the study sample included individuals beyond their 5th decade, which might explain the higher mean TK compared to the study on adolescents (Korovessis et al. 2002), there was only one subject aged over 60 years and therefore the effect of age in the present sample would be expected to be minimal. Interestingly, the 61-year-old female assessed in the present study had a mean baseline TK over 90˚, which appears extreme compared to the other normative surface curvature studies described here. This case would have impacted on the mean for this small group of 11 subjects. Further, it might be speculated that an inclusion of more cases over 60 years would result in age-related differences in TK.

The results of the present study showed a large individual variation in kyphotic angle (38.2˚ to 93.2˚), which may reflect normal variation in thoracic posture and perhaps a non-uniform effect of aging between individuals. Factors known to influence thoracic curvature include occupation and activity levels (Sugahara et al. 1981) and bone mineral density (Goh et al. 1999a). These may have been factors affecting the healthy cases followed in this study however specific details along these lines were not captured.

Pelvic incidence: The present study showed an initial mean PI of 21.4˚ (±6.2˚) for the mixed group of 11 healthy volunteers. At the 6 week and 6 month time-points this had significantly increased by less than 1.5˚, returning back to baseline levels at one and two years later. Bullock-Saxton (1993) demonstrated differences in pelvic tilt assessed from the surface over a 16-month period in healthy young women, with a subsequent return to baseline values by 24 months. Their method differed by using the angle with the horizontal that a line between the anterior superior and posterior superior iliac spines made, for their determination of pelvic inclination. This measurement was arguably more indicative of iliac and therefore pelvic position than the posterior sacral angulation compared to the vertical that the present study utilised. Both studies however agree in observing variability in PI within a two-year period.

Women in the present study had significantly more pelvic incidence (24.7˚ ±6.4˚) compared to the five male cases (17.4˚ ±3.0˚) that were more homogenous. In assessing 90 asymptomatic 40-69 year old adults of equal gender number, Youdas et al (1996) reported similar PI, as measured from the surface with an inclinometer, to the present study for their female (22.8˚ ±7.6˚) and male (13.8˚ ±4.5˚) subjects. They did not indicate the significance of the difference between genders however it would be reasonable to speculate that the difference was statistically significant ($p<0.05$). Subjects aged 35 years or more in the present study had greater PI (24.1˚ ±6.1˚) than their younger counterparts (19.1˚ ±5.2˚).

Sagittal balance: The present study reported an initial mean (SD) SB of 26.6mm (±24.5) for healthy volunteers of a wide age range. Over the initial 6 months of follow-up, SB for this group of 11 healthy adults initially increased and then decreased compared to baseline, but was equivalent again after one and two-years. This finding suggests that while the capacity for intra-individual variability does exist during the short term, SB remains reasonably similar over a two-year period. Sagittal alignment of the asymptomatic adult spine and pelvis is reported to be highly variable between individuals (Stagnara 1982; Bernhardt and Bridwell 1989; Jackson and Hales 2000; Vaz et al. 2002; Vialle et al. 2005; Gangnet et al. 2006), with an offset of the SVA beyond 25mm either anterior or posterior to the plumbline, considered beyond normal (Jackson and McManus 1994). The results of the present study are in excess of this with the mean SB being 26mm and the potential for double that range into forward leaning based on a value one SD (24mm) from the mean. The 11 healthy volunteers used in this study on average lean forward to the outer boundary of what Jackson and McManus (1994) consider normal.

Investigations assessing this parameter have determined the position of the sagittal vertical axis from full thoracolumbar plain lateral radiographs, therefore have referenced skeletal shape captured at an instant, rather than that derived from the back surface over 5 minutes (averaged per session) as in this rasterstereographic component of this thesis study. Based on the known variability to trunk inclination that postural sway represents (Appendices VII.1&2), the results reported in these cases appear reasonable; however no known literature reports sagittal balance based on surface curvature derived from the skin, to provide additional information. Force-plate technology appears to be attracting wider use in combination with radiographic and surface topographic methods for deriving spinal curvature in order to account for the effects of postural sway on sagittal alignment (Van Royen et al. 1998; Winter et al. 2001; Vaz et al. 2002).

Integrating force-plates into surface curvature assessments with rasterstereography may represent a more accurate method of capturing posture information using the instrument.

5.4.2 Relationships between variables

Pelvic incidence and sagittal balance: The strongest relationship between variables found in the present study was between PI and SB (Rho=0.88), which is not surprising given both variables are derived with reference to the systems internal vertical and based on distal landmarks in the sacral region (Figure 3.3). Unfortunately no studies reporting comparable methods to the present investigation have described sagittal balance in relation to the SVA determined from the skin surface. Consequently, it is difficult to draw strong conclusions based on the present study in isolation. Investigations reporting on skeletal curvature indicate that spinal and pelvic balance centres around the axis of the hip in order to effectively position the line of gravity over the femoral heads (Vaz et al. 2002; Roussouly et al. 2006). The variables PI and SB therefore appear related and the strong correlation reported in the present study, would seem a reasonable reflection of normal standing posture.

Lumbar lordosis and thoracic kyphosis: A moderate relationship between LL and TK was found in this study (Rho=0.76; p<0.01), which appears in agreement with others reporting on spinal curvature as determined from the skin surface (O'Gorman and Jull 1987; Bernhardt and Bridwell 1989; Vedantam et al. 1998; Jackson and Hales 2000). Based on skeletal measurements of spinal curvature from plain lateral radiography, Gelb et al (1995) found that increasing age resulted in loss of distal lordosis without a compensatory increase in TK (Gelb et al. 1995). This indicates potential for divergence between the two variables with older age and may highlight the capacity for a weaker relationship between LL and TK in older groups.

Lumbar lordosis and pelvic inclination: The present study revealed a fair but insignificant relationship between LL and PI (Rho=0.40; NS). That a stronger correlation did not exist is interesting given rasterstereography references tangents defined by the same lumbosacral inflexion when deriving both variables. Unfortunately only a limited literature reports pelvic inclination and lumbar lordosis as variables derived from the skin surface. Two studies that assessed surface spinal curvature using the flexirule describe only weak association between surface-derived PI and LL in asymptomatic standing subjects (Walker et al. 1987; Youdas et al. 1996). In contrast, studies based on vertebral landmarks report a moderate to strong relationship (r=0.65-0.90) between the two variables (Stagnara 1982; Voutsinas and MacEwen 1986; Duval-Beaupere et al. 1992; Jackson and McManus 1994; Vedantam et al. 1998; Vaz et al. 2002; Vialle et al. 2005). This appears intuitive considering the lumbosacral angle, which is influenced by sacral inclination, contributes most to regional lumbar curvature (Stagnara 1982; Jackson and McManus 1994). When comparing surface versus skeletal spinal curvature, derived shape is reported to be most divergent in the lumbosacral region where the thoracolumbar fascia and subcutaneous soft tissues are thickest (Refshauge et al. 1994; Mannion et al. 2004). This concept is explored further and supported by the study reported in Appendix VIII.3, and may explain the weak relationship between LL and PI noted in this and other surface assessment studies.

5.4.3 Physiological influences on posture

To amplify the observations in this study of 11 healthy volunteers over 24 months it was considered helpful to examine influences on sagittal curvature and alignment in standing, particularly those that might impact on results obtained for individuals. The influence of arm positions on postural sway and lumbar spinal curvature were assessed in the studies reported in Appendices VII.1-3. Some aspects of these studies have already been briefly introduced. The combined findings of the collateral investigations were that: arm position did not influence the range of postural sway, which was variable and greater in the anteroposterior, compared to the mediolateral plane; increased LL occurred when the arms were at 90˚ elevation as compared with them being held by the side or in the clavicle position; a shift toward negative sagittal balance occurred with increasing arm elevation; PI reduced at the 90˚ shoulder elevation when compared with the other two arm positions; and no change in TK was noted between arm positions.

In assessing surface curvature in the eleven healthy volunteers reported here in Chapter 5, subjects were asked to position their arms comfortably by the side. In contrast, the surgical patients reported in Chapters 6 and 7.2 were imaged for both surface and skeletal assessments of curvature with their arms in the clavicle position. Therefore any potential influence of alternative arms position on thoracolumbar curvature would be most likely for the surgical cases rather than the healthy volunteers. As such, further elaboration of the influences of these physiological variables is discussed later in relation to the surgical cases (Chapter 8).

In assessment of human performance and biological parameters, single measurements rarely provide sufficiently accurate data to allow for serial comparisons. In the present study the author elected to perform 5 repeat intra-session rasterstereographic trials per person in order to appreciate the repeatability of each parameter as determined through this instrument. This methodological approach afforded a comparably more extensive data set than would have been achieved if single images were used per time-point. The averaged intra-session values derived for use in this study were therefore considered to more reasonably account for any variability that may have been introduced by normal physiological postural sway. This might be an approach that other investigators elect to adopt when employing surface topographical instruments to report surface curvature in the absence of force-plate stabilometry.

Skin surface measurements derived from the midline surface contour, particularly those requiring tactile application; follow the line of the spinous processes and any overlying subcutaneous tissue, which Mannion et al (2004) suggest is most notable in the lumbar region towards the sacrum. A collateral investigation comparing rasterstereographically-derived surface lumbar contour and radiographically-derived skeletal lumbar curvature, which were both measured concurrently in a cohort of older women, was undertaken by the author to explore any measured difference in curvature between the skin surface and the skeletal spine. This study is presented in Appendix VIII.1 and was used in addition to another investigation assessing the intra-regional sagittal dimensions of lumbar vertebrae (Appendix VIII.2) to assess the relationship between surface and skeletal contours in the lumbar region. A further study measured subcutaneous tissue depth along the thoracolumbar spine to provide additional data (Appendix VIII.3). These three investigations, which additionally describe aligned published work, attest to the divergent shape of both skin surface and vertebral body contours in the lumbar spine, which represents the poorest correlation of all spinal regions (Willner 1981; Refshauge et al. 1994; Goh et al. 1999a). The results described in this chapter, which report surface thoracolumbar curvature in healthy volunteers, should be reasonably comparable to other investigations assessing surface curvature. However, they may not be best evaluated alongside studies assessing skeletal curvature from radiography, when surface curvature underestimates that derived from the vertebra.

5.5 Conclusions: Healthy Volunteers

Eleven healthy volunteers of a wide age range showed no change in their lumbar lordosis and thoracic kyphosis within a two-year period, while pelvic incidence and sagittal balance were variable. Gender differences in lumbar lordosis, pelvic incidence and thoracolumbar sagittal balance were observed, with no difference noted for thoracic kyphosis. Lumbar lordosis and pelvic incidence were greater in women than men. Sagittal balance was more positive in women. Strong and moderate relationships were found between pelvic incidence and sagittal balance, and lumbar lordosis and thoracic kyphosis, respectively.

CHAPTER 6

The effect of interspinous implant surgery on back surface shape and radiographic lumbar curvature

6.1 Introduction

Surgical correction of lumbar spine disease using the DIAM^{TM} interspinous implant (Medtronic Sofamor Danek, Memphis, USA), has the potential to alter lumbar lordosis when a relative segmental kyphosis at implant-level is induced (Taylor et al. 2007) (Figure 2.11). This silicone-based dynamic spacer is purported to alleviate back and leg pain through an induced interspinous distraction, which is said to reduce axial compression of pain-sensitive or space-occupying degenerative structures (Taylor et al. 2007). Despite its continued use in the surgical treatment of lumbar pathology, particularly those affecting the posterior elements, a limited literature describes its effect on physiological skeletal and postural alignment (Phillips et al. 2006; Kim et al. 2007). Preservation of regional sagittal balance during lumbar and lumbosacral surgery is the ideal, with restoration of normal thoracolumbar alignment considered key to a successful outcome (O'Shaughnessy and Ondra 2007). Whether either segmental kyphosis or regional curvature compensation occurs after surgery with the DIAM interspinous implant remains undetermined. There exists a need to assess posture curvature changes following lumbar DIAM surgery to better appreciate the short and long term effect on skeletal and surface lumbar curvature.

An objective of the present study was to provide a preliminary assessment of the reproducibility of lumbar lordosis measurements from rasterstereographic back shape analysis in healthy volunteers of different ages, and in patients who underwent lumbar surgery augmented with a single or multi-level DIAM interspinous implant(s). Surgery subjects received pre- and 6 week’s post-operative radiographic imaging as part of their routine surgical management and therefore skeletal and surface lumbar curvature for the surgery subjects were compared between the two time-points. Healthy subjects were recruited to gauge the repeatability of rasterstereography in surface lumbar lordosis measurement and did not undergo radiographic assessment. The influence of lumbar surgery augmented with the DIAM interspinous implant on regional and segmental curvature was assessed in a preliminary subset of the surgery cases examined in the main investigation. Based on literature describing the effect of a DIAM implant (Taylor et al. 2007), it was anticipated that there would be an initial flattening of the lumbar spine following this surgical procedure, particularly at the implanted level.

6.2 Methods

6.2.1 Study sample:

The study sample comprised 10 healthy volunteers [6 females, 4 males; aged 22 to 61 years; mean 35.8 (SD 14.3)] and 10 patients who were scheduled for lumbar spine surgery [5F, 5M; aged 31 to 65 years; mean 51.4 (SD 10.5)]. The DIAM interspinous implant (Medtronic Sofamor Danek, Memphis, TN, USA) was used to augment concurrent lumbar surgery, which included either: laminotomy; microdiscectomy, or interlaminar central and lateral recess decompression procedures. Institutional ethics approval was obtained [Appendix II.2] and subjects provided written consent to involvement in the study [Appendix I.2].

6.2.2 Surface curvature (Rasterstereography):

Back shape imaging was performed utilising the Jenoptik Formetric video rasterstereography imaging system (Aesculap Meditec GmbH, Germany). Key features of the rasterstereographic evaluation of back sagittal profile have been illustrated previously in Figures 2.x and 3.x. The system derived maximum lordosis spanning the thoracolumbar (ITL) to the lumbosacral inflexion points (ILS) which are photogrammetrically derived via contours and anatomical landmark recognition based on the subject's surface posture (Drerup and Hierholzer 1987b) (Figure 6.1). The protocol used to derive the rasterstereographic images has been described in Chapter 3.6.4, and in Chapter 5 for the normal cases. The six week time-period was selected to match the routine imaging protocol as practised by the collaborating neurosurgeon for assessment of spinal alignment after DIAM surgery.

6.2.3 Skeletal curvature (Radiography):

The radiographic procedure was applied to the surgical cohort only, as a component of their routine surgical work-up for establishing alignment, the method of which has been described earlier in Chapter 3.6.5. Lordotic angle was derived via the modified Cobb method (Singer et al. 1994) using the superior end-plates of L1 and S1 for reference. Disc angle at the single or primary pathological level implanted with a DIAM was recorded as the intersection of the tangents between the inferior end-plate of the upper vertebra, and the superior end-plate of the lower vertebra (Stagnara 1982) (Fig. 6.1).

6.2.4 Surface versus skeletal curvature: Surgery subjects:

Rasterstereographic measurements of lumbar lordosis were obtained from each surgical subject, with the mean of 5 trials compared with the lumbar lordosis angle obtained from their lateral lumbar spine plain radiographs. Rasterstereographic and radiographic imaging techniques for the surgical cohort were employed within 24 hours of each other.

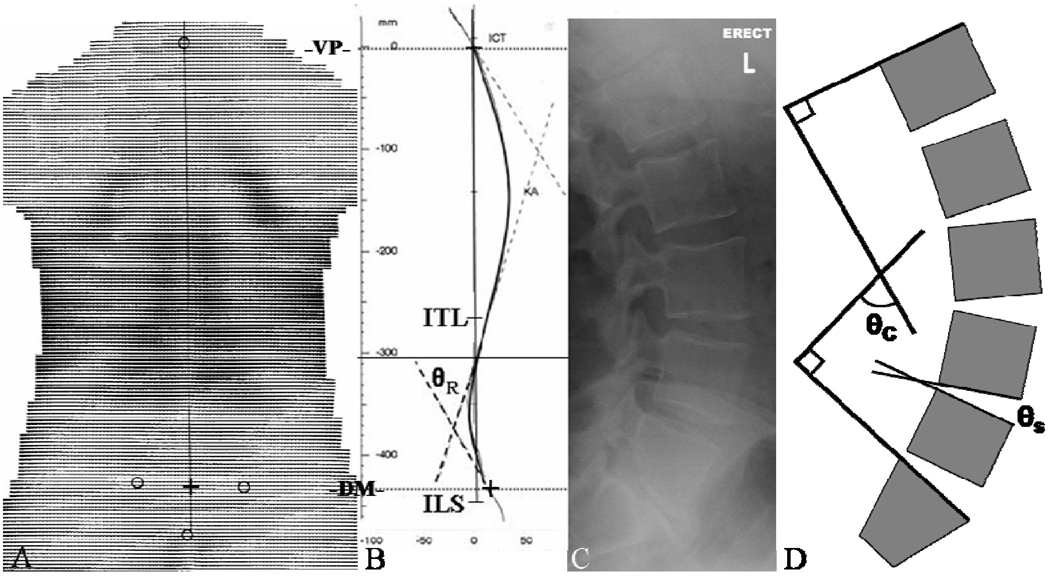


Figure 6.1: (A) Rasterstereography transverse profile derived from a 38 year old healthy female subject demonstrating automatic landmark locations (marked by small circles); (B) Sagittal profile for the thoracolumbar curvature where lordosis (θR) is derived from the angle created between the thoracolumbar inflexion point (ITL) and the lumbosacral inflexion point (ILS); (C) Erect lateral radiograph and schematic outline of lumbar vertebral bodies highlighting the four-line modified Cobb angle (θC) method for determining lumbar lordotic angle (D). Tangents are drawn from the superior end-plates of L1 and S1; perpendiculars from the tangents create the angle θC. Segmental angle (θS) is derived from tangents through the inferior end plate of the top vertebra, and the superior endplate of the adjacent one.

Reliability of lordosis derived from rasterstereography for each normal and surgical subject was assessed with descriptive statistics. Standard deviation and change scores represented intra- and inter-session curvature variability for each subject. Wilcoxon's Signed Rank test was used to establish the significance of the differences in lumbar lordosis or disc angle for the normal and surgical subjects between time-points. Comparisons between lumbar lordosis derived from rasterstereography versus erect lateral radiography were assessed using the nonparametric correlation coefficient Spearman's rho (ρ). A probability of $p<0.05$ was used as the criterion to represent meaningful differences.

6.2.5 Repeatability:

1. Rasterstereography

To examine the intrinsic reliability of the rasterstereographic imaging system, a thermoplastic back phantom manufactured from a young volunteer (Goh et al. 1999b), was imaged five times on two occasions, six weeks apart. Mean lumbar lordosis (SD; range; CV%) at baseline for the phantom was 26.4 degrees (0.14; 26.1 – 26.5; 0.6%) and 26.1 degrees (0.05; 26.1 – 26.2; 0.2%)

at six weeks (NS). These results confirm the reproducibility of lumbar lordosis as measured by rasterstereography for a phantom model of fixed surface contour. Descriptive statistics were used to present the variability in lumbar lordosis as achieved with rasterstereography within each 5-trial session, and between the 6 week time-points, for both the healthy and surgical subjects.

2. Radiography

Intra-rater repeatability of the measurements derived from radiographic imaging was assessed in two ways. The first, using 10 repeated measurements of a single surgical case's baseline image on two occasions to coincide with the subject's preoperative and six weeks postoperative time-points; and secondly, through repeated measurements of each of the 10 surgical subjects' baseline images, again, with a six week interval. The mean lumbar lordosis (SD; CV%) as derived from the same single image, was 65.5 degrees (1.9; 3.0%) at baseline, and 66.4 degrees (1.9; 3.0%) at it's repeat at six weeks (NS for difference). Mean implanted segmental disc angle was measured for the single subject's image (10 repeats) to be 8.1 degrees (1.3; 16.0%) and 8.0 degrees (0.6; 8.0%) (NS for difference) at baseline and 6 weeks, respectively. Repeat 10-subject baseline measurements revealed no significant difference between either lumbar lordosis ($p=0.89$), or primary segmental angle ($p=0.48$) over the six week interval. The least significant changes for lordosis and segmental angle were 3.7 and 3.6 degrees, respectively.

6.3 Results

Mean lumbar lordosis angle (θ_R), standard deviation (SD) and coefficient of variation [CV%] for rasterstereography of 10 healthy subjects and 10 surgical cases measured at two time-points six weeks apart, are shown in Table 6.1.

For healthy subjects, five-trial means of lordosis angle varied between 27.3 and 69.8 degrees at baseline (mean 46.0; SD 11.7). At six weeks the variation was between 29.0 and 69.7 degrees (mean 45.4; SD 11.8).

Individual CV%, representing intra-session lordosis variability, ranged between 0.3 and 5.2% across both time-points (mean 2.2; SD 1.4). Change to lumbar lordosis between time-points for normal subjects was -0.6 degrees (range -3.9 to 3.6) representing no flattening (NS; $p=0.58$ for all 50 measurements) (Fig. 6.2). Averaged absolute change, irrespective of direction, was 1.9 degrees. Pre-operative mean lordosis (θ_R) as measured via rasterstereography for the surgical cases, ranged between 31.2 and 68.5 degrees (mean 46.2; SD 11.5) and from 32.3 to 54.6 degrees (mean 43.1; SD 7.6) at their six week post-operative time-point.

Table 6.1: Repeatability of assessing lumbar lordosis as measured in degrees by rasterstereography for 10 healthy subjects, and 10 lumbar surgery cases. Individuals were imaged five times, on two occasions, baseline/pre-operatively, and 6 weeks/postoperatively. Changes to surface lordosis between time-points for both healthy and surgery cases are represented as change scores (△) where a negative value represents flattening of the lumbar curvature.

Healthy						Surgery					
n	F/M	Age	Base Raster Lordosis	6week Raster Lordosis	Raster △ θ_R	F/M	Age	DIAM N°	Base Raster Lordosis	6week Raster Lordosis	Raster △θ_R
1	F	22	56.1 (1.7) [3.0][1]	56.2 (1.3) [2.2]	0.1	F	53	2	47.9 (0.9) [1.8]	46.7 (1.0) [2.1]	-1.2
2	F	27	48.3 (1.3) [2.6]	47.9 (0.2) [0.3]	-0.4	F	56	3	53.5 (0.5) [0.9]	46.7 (0.4) [0.9]	-6.8
3	F	38	45.6 (1.3) [2.9]	42.8 (1.1) [2.5]	-2.8	F	57	1	54.9 (1.8) [3.3]	51.0 (1.1) [2.2]	-3.9
4	F	40	42.3 (0.8) [1.8]	45.9 (1.0) [2.3]	3.6	F	58	1	51.6 (1.2) [2.2]	47.3 (1.0) [2.1]	-4.3
5	F	58	50.7 (2.6) [5.2]	51.1 (0.9) [1.7]	0.4	F	65	3	68.5 (0.7) [1.0]	54.6 (1.0) [1.8]	-13.9
6	F	61	69.8 (0.4) [0.5]	69.7 (0.2) [0.5]	-0.1	M	31	1	45.2 (1.1) [2.5]	41.9 (0.6) [1.4]	-3.3
7	M	22	39.3 (0.4) [0.9]	36.0 (0.6) [1.5]	-3.3	M	37	1	31.2 (0.7) [2.1]	32.3 (0.6) [1.9]	1.1
8	M	24	34.9 (0.5) [1.4]	33.5 (0.3) [1.0]	-1.4	M	47	1	36.1 (0.7) [1.9]	42.4 (0.5) [1.2]	6.3
9	M	27	46.0 (1.1) [2.5]	42.1 (1.9) [4.6]	-3.9	M	51	1	40.4 (0.5) [1.2]	35.9 (0.2) [0.6]	-4.5
10	M	39	27.3 (0.9) [3.4]	29.0 (1.1) [3.8]	1.7	M	59	3	32.8 (0.5) [1.4]	32.7 (0.6) [2.0]	-0.1
		35.8 (14.3)	46.0 (1.1) [2.4][2]	45.4 (0.9) [2.0]	-0.6 (2.3)[3]		51.4 (10.5)		46.2 (0.9) [1.8]	43.2 (0.7) [1.6]	-3.1 (5.3)[4]

[1]Mean (SD of five-trial measurements for each subject) [CV% of five-trial measurements for each subject]; [2] Mean (average SD for 10 subjects) [average CV% for 10 subjects]; [3] NS; [4] P<0.01; Raster=rasterstereography; θ_R=lumbar lordosis as derived using rasterstereography; Xray=radiography; Base=baseline/preoperatively; DIAM N°=number of DIAMs implanted in subject

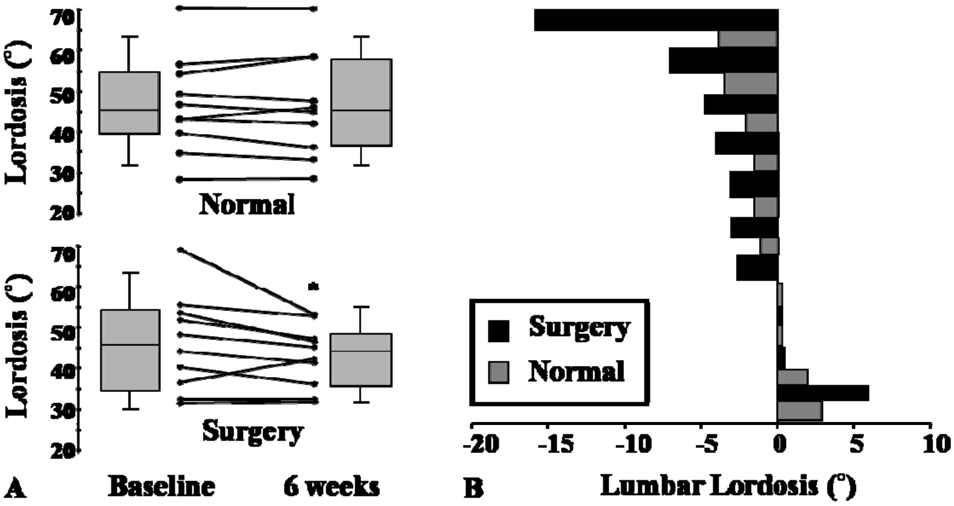


Figure 6.2: (A) Mean lumbar lordosis angle (θR in degrees) for 10 healthy and 10 DIAM surgery cases as measured by 5 replicate trials using rasterstereography at baseline or pre-operatively, and six weeks later/post-operatively. A significant reduction (*; p<0.01) in lordosis, as determined by Wilcoxon's signed rank test, is depicted in the surgical cohort. Box-plots reveal summarised data where horizontal lines from the top represent 10th, 25th, 50th, 75th and 90th percentiles, respectively. (B) Histogram representing change (in ranked order) to lumbar lordosis (˚) for surgical and healthy cases, demonstrating overall wider change in the surgical subjects.

Individual CV% representing intra-session lordosis variability for the surgical cohort, ranged between 0.6 and 3.3% across both time-points (mean 1.8; SD 0.6). Reduction in mean lumbar lordosis between time-points was significant at -3.1 degrees (range -13.9 to 6.3 degrees) ($p<0.01$ for all 50 measurements), and 4.7 degrees when direction was ignored. The post-operative flattening of lumbar curvature for the surgical group has been presented in Figure 6.2. Measurements of lumbar lordosis (θ_C) and primary implanted disc angle (θ_S), as determined from standing lateral plain radiography (skeletal measurement) in the ten lumbar surgery subjects measured preoperatively and 6 weeks postoperatively, are presented in Table 6.2. When change in curvature was examined, a trend for flattening of lumbar lordosis (mean -3.0˚, SD 5.2, $p=0.14$) was observed over the 6 weeks. The reduced disc angle (mean -1.2˚, SD 4.2) was not significant between time-points.

Further inspection of Tables 6.1&2 reveals that surface lumbar curvature increased in 2/10 surgical subjects receiving lumbar surgery, both of whom were augmented with a single DIAM, while skeletal curvature showed either an increase (3/10) or no change (1/10) in the presence of DIAM. Disc angle at the primary segmental level implanted with a DIAM for each surgical subject, was shown to increase in 3/10 cases. Change in surface and skeletal lumbar lordosis according to the number of DIAMs implanted has been presented in Figure 6.3. This shows a trend for more flattening in cases with multiple implants compared to those receiving a single DIAM.

Table 6.2: Radiographic values obtained at both time-points for skeletal determination of lordosis (θC in degrees; L1 to S1 Cobb method) and segmental disc angle (primary implanted level; θS in degrees) in the surgery cohort. Changes in lordosis ($\triangle\theta C$) and primary disc angle ($\triangle\theta S$) between time-points for skeletal curvature are represented as change scores, where a negative value represents flattening.

	F/M	Age	DIAM N°	1° Level	Base θ_C	6wk θ_C	$\triangle\ \theta_C$	Base θ_S	6wk θ_S	$\triangle\ \theta_S$
1	F	53	2	L5/S1	65	67.5	2.5	-0.5	4.5	5.0
2	F	56	3	L5/S1	70	68	-2	3.0	3.0	0
3	F	57	1	L4/5	45	39	-6	5.0	1.5	-3.5
4	F	58	1	L4/5	62	59	-3	3.0	3.0	0
5	F	65	3	L5/S1	49	49	0	11.5	18.0	6.5
6	M	31	1	L5/S1	60	63	3	12.5	9.5	-3.0
7	M	37	1	L4/5	42	45	3	3.0	1.0	-2
8	M	47	1	L4/5	68	62	-6	8.0	4.5	-3.5
9	M	51	1	L5/S1	60	48	-12	11.0	3.5	-7.5
10	M	59	3	L4/5	43	34	-9	13.5	9.5	-4.0
Mean	51.4				56.4	53.5	-3.0 (5.2)[1]	7.0 (4.9)	5.8 (5.1)	-1.2
(SD)	(10.5)				(10.7)	(12.1)				(4.2)[2]

DIAM N°=number of DIAMs implanted in subject; 1° Level=primary segmental level implanted with a DIAM; Base=preoperative; 6wk=6weeks postoperatively
[1] NS. *P*=0.14.
[2] NS. *P*=0.44.

The association between lumbar lordosis as derived separately from rasterstereography and radiography showed a poor correlation pre-operatively (ρ=0.28; NS) and post-operatively (ρ=0.26; NS). However, strong associations for pre- versus post-operative lordosis, assessed by rasterstereography (ρ=0.94; p<0.01) or radiography (ρ=0.87; p<0.01), were evident. These findings are presented in Figure 6.4.

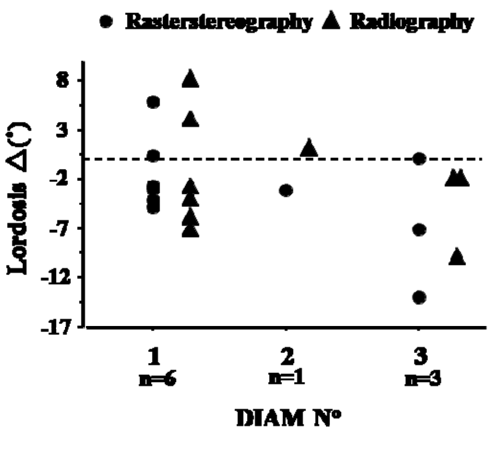


Figure 6.3: Change in surface (rasterstereography) and skeletal (radiography) measurements of lumbar lordosis (LL) according to the number of devices implanted per case, in 10 subjects who underwent DIAM-augmented surgery in treatment of their lumbar spinal pathology. Those receiving 3 DIAMs appeared to demonstrate a more flattened LL compared to those receiving a single implant.

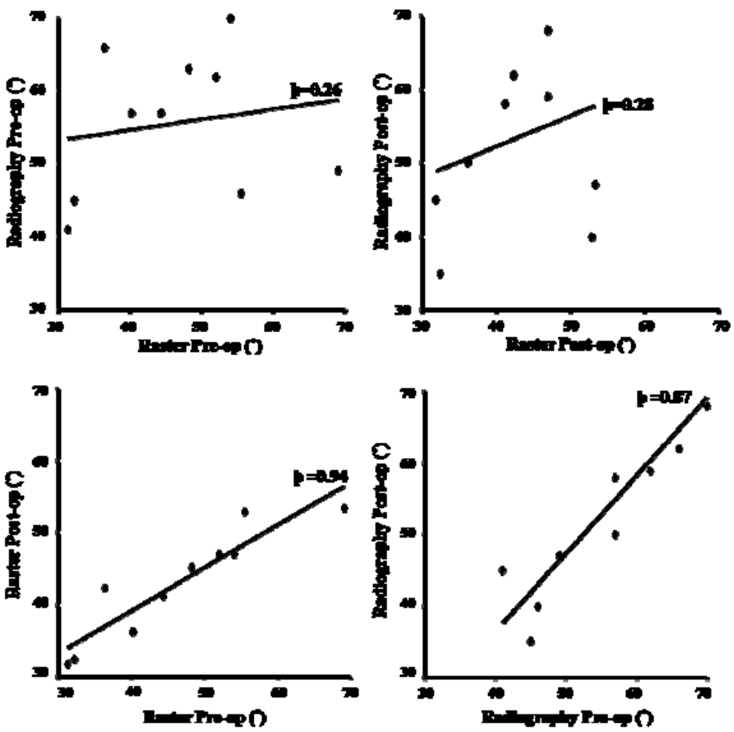


Figure 6.4: Scatter-plots indicating poor association between measurements of lumbar lordosis from the surface employing rasterstereography (raster) versus skeletally as determined via plain lateral radiography, both preoperatively and postoperatively. Pre- and postoperative values as determined by each method were also compared with strong relationships found.

6.4 Discussion

This study demonstrated highly reproducible intra-session and short-term (six weeks) surface-derived measurements of lumbar lordosis from rasterstereographic back shape imaging in erect standing healthy volunteers spanning a wide age range. Since the short-term change in this group was NS (<1˚, Table 6.1), the prospect of applying this modality to patient groups for the purposes of non-radiographic serial lumbar lordosis measurement is encouraging. The use of this system for spinal curvature analysis has primarily involved studies assessing scoliosis and thoracic kyphosis (Drerup and Hierholzer 1987a; Goh et al. 1999b,a), with the results of the present study confirming its clinical utility for use in lumbar spine curve assessment. For ethical reasons, radiographic imaging could not be used for skeletal assessment in these healthy subjects.

In this study, the mean change in lordosis in healthy subjects as measured by rasterstereography over a six week period was not significant (0.6˚ decrease, Table 6.1). Therefore it is reasonable to assume that any serial change exceeding 1˚ as determined by this method may be due to factors other than random variation. Further, a comparison of Table 6.1 data reveals that the intra-subject variability for lumbar lordosis measurement was not greater in surgical patients than for the healthy subjects. These results confirm the repeatability of the erect standing posture, suggesting similar intra-session variability in surface lumbar lordosis between healthy and lumbar surgery subjects.

Flattening of lumbar lordosis after surgery augmented with a DIAM interspinous implant was shown in the surgical group, where the surface measure revealed a reduced angle; -3.1˚ (Table 6.1). The significant surface lordosis flattening as measured using rasterstereography, confirms the effect of DIAM surgery in the lumbar spine as proposed by Taylor et al (2007), yet the insignificant ($p=0.14$) (although comparable; -3.0˚) skeletal changes raise questions about the purported biomechanical effect of the device. Additionally, there were cases where an increased surface or skeletal lordosis was shown, suggesting the need for further investigation into the local and regional effects of this device. The results indicated in Figure 6.3 suggest that the number of DIAMs implanted may influence skeletal curvature, with more devices leading to greater reduction in the lordosis. Although this finding appears intuitively reasonable, the limited dataset studied in this preliminary series weakens the power of making conclusions regarding the influence of DIAM number on spinal curvature. This is addressed further in Chapters 7.2 (surface) and & 7.3 (skeletal) where the results of more subjects are reported.

The clinical protocol employed for surface assessment of lumbar curvature in this study, used five quick replicate rasterstereographic measurements for the derivation of lordosis at each time-point. This may have improved the precision of the lordosis data attained, perhaps indicating an advantage of the non-ionising rasterstereographic technique for curvature assessment, over a radiographic one. The subtle surface curvature change revealed in the surgical cases, may be due primarily to: low back or leg pain, the surgical intervention, use of a DIAM interspinous implant, or post-operative rehabilitation and recovery, in combination or in isolation. The 6 week time-point represents a short assessment period in the post-operative course of a lumbar surgery patient. Whether change occurred over a longer post-operative course is reported in Chapter 8 & 9.

Two potential sources of measurement variability should be considered when using rasterstereography: inaccuracies within the imaging system and variations in subject posture. Repeated imaging of the plastic back phantom, where postural influences were eliminated, resulted in negligible variability in derived measures. This result confirmed the high degree of intrinsic precision associated with automatic landmark localisation from rasterstereography as previously described by (Drerup and Hierholzer 1987b). The repeatability of lumbar lordosis as derived using rasterstereography compared well with those achieved for measurements derived from radiographic imaging. Both methods revealed similar intra-session/image measurement variation.

Postural sway is a normal physiological phenomenon occurring during standing, and is known to increase with back pain (Byl and Sinnott 1991; Hamaoui et al. 2004; Smith et al. 2005). Whether sway contributed to the variability of lumbar lordosis angle, as measured by rasterstereography or radiography in both cohorts, is beyond the scope of this study; however its potential is acknowledged. The present study supports the use of rasterstereography in assessing lumbar spinal curvature in low back surgical patients, although the clinical relevance of the modest observed changes from either method in this cohort is questioned.

Caution should be applied when comparing absolute values for surface (rasterstereography) and skeletal (radiography) measures of lumbar lordosis. Surface measures will reference contours formed by spinous processes and overlying subcutaneous tissue. In contrast, radiographic measures are derived directly from the vertebral body end-plates. Given that there is anatomical variation in the distance between the spinous process and posterior vertebral body line, it is unreasonable to expect a direct equivalence of surface and skeletal measures. As a consequence, surface curvature analysis tends to yield lower values for lumbar lordosis than those for radiography. The poorer correlation between surface and skeletal lumbar lordosis revealed in this study is less than has been reported previously in the thoracic spine (Goh et al. 2000) and suggests a more notable difference between surface and skeletal curvature in the lumbar, as compared to the thoracic region.

6.5 Conclusions

Reproducible measurement of lumbar lordosis was derived from rasterstereographic back shape imaging in healthy volunteers and lumbar surgery patients spanning a wide age range. The results confirm reproducibility of the erect standing posture in healthy and symptomatic back pain individuals. Time-dependent lordosis variation in healthy subjects was not statistically significant, supporting the robustness of the technique for serial studies. A demonstrable yet inconsistent reduction (n=7/10) in surface lumbar lordosis was shown in a lumbar surgical cohort between their pre- and post-operative time-points. The association between skeletal and surface lumbar lordosis was poor. The number of DIAMs implanted may represent a confounder in any noted change to lumbar angulations.

CHAPTER 7

Patient-reported outcomes after surgery augmented with DIAM interspinous implant

7.1 Introduction

The main aim for this chapter was to test the study hypotheses (#1&2; p75) relating to the effectiveness of DIAM surgery in improving patients pain and function over a two year postoperative period, and according to MID definitions (previously described in Chapters 2 & 3). Hypothesis 1 predicted that there would be time-dependent clinically important improvement in patient-reported pain and function over a two year postoperative period. Hypothesis 2 predicted that cases with pathology affecting the zygapophysial joint(s) would have superior improvement in pain and function compared to cases with predominant disc disease. Various studies have reported the successful use of the DIAM in lumbar degenerative disease (Caserta et al. 2002; Schiavone and Pasquale 2003; Mariottini et al. 2005; Taylor et al. 2007; Guizzardi and Petrini 2008; Sobottke et al. 2009), however no common outcome instrument has been used by authors to allow for comparisons between studies. The prospective arm of this thesis investigation employed a patient-reported HRQoL questionnaire that was compiled based on expert recommendations for low back pain-related research (Deyo et al. 1998; Bombardier 2000). Consequently, it was believed that results would have a wider application to existing literature reporting other interventions managing low back disorders. Whether noted changes were clinically important and/or time dependent would test the first hypothesis. Additionally, the retrospective audit of prospectively collected outcomes data that constituted Phase I of the present study (Crawford et al. 2009a) (Chapter 4), provided initial insight into categories of patients that showed superior improvement postoperatively. Cases with facet-predominant spinal disease responded significantly better than those with problems centred at the disc.

Another important aspect of this thesis investigation was to contribute to informing clinical guidelines for the use of the DIAM in lumbar pathologies. Reviews describing ISP technologies suggest a broadening array of clinical indications for their use (Christie et al. 2005; Bono and Vaccaro 2007; Crawford et al. 2009c). Lumbar spinal stenosis has emerged as the key indication, particularly for the X-Stop (Table 2.3), when in the presence of neurogenic intermittent claudication that is relieved by positions involving lumbar flexion. The use of ISP devices in disc-related pathologies like degeneration and recurrent herniation, represent relatively new and as yet unsubstantiated indications. Literature reporting surgeries employing the DIAM remain limited, generally to retrospective observational series (Table 4.1) that describe several pathologies for which the device is purportedly effective. Most studies reporting on the DIAM do not provide data to distinguish between cases with different diagnoses or pathologies. No known published studies were identified that compare outcomes of patients with different pathologies after DIAM-based surgery, to indicate its best application. Consequently, this chapter analysed the data using the anatomical and diagnostic sub-groups within the cohort of 81 prospective-phase cases. In addition, other potential prognostic determinants were examined to improve the identification of suitable patients, preoperatively.

7.2 Methods

The methods employed in this chapter were previously outlined in Chapter 3. Eighty-one cases [37 females, 44 males; mean (SD) age 51.7 yrs (13.5)] from the prospective phase of the study were assessed for their self-reported response (via questionnaire) to the DIAM-augmented surgery. Questionnaires were completed at seven predetermined time-points [B, 6w, 3m, 6m, 12m, 18m, 24m] over a two year postoperative course. Gender and age details for the cohort have been outlined earlier (Chapter 3). In relation to the preoperative classifications performed by the surgeon, anatomical categorisation showed predominant (>50%) involvement of the disc in 46 (of 81) cases and the facet in 26 (of 81), with nine cases having equal involvement of disc and facet degeneration. Clinical indications for surgery were: foraminal stenosis (FS; n=43), central canal stenosis (CS; n=6), facet joint pain syndrome (FJPS; n=10) and degenerative spondylolisthesis (DS; n=22). Case numbers according to the preoperative classifications are presented in Table 7.1.

Table 7.1: Subject numbers according to gender, age (<50yrs≤), and preoperatively defined anatomical and diagnostic categories, for 81 patients who underwent lumbar surgery augmented with DIAM in treatment of their lumbar spine pathology.

	Sub-groups	**Females**	**Males**	**Total**
Gender		37	44	81
Age	<50	11	21	32
	≥50	26	23	49
Anatomical	Disc	18	28	46
	Facet	14	12	26
	Mixed	5	4	9
Clinical Diagnosis	Foraminal Stenosis	16	27	43
	Central Canal Stenosis	3	3	6
	Facet Joint Pain Syndrome	5	5	10
	Degenerative Spondylolisthesis	13	9	22

A detailed description of the: statistical methods employed, treatment of missing data, MID definitions used, and classification of responder groups [absolute versus normalised for baseline; moderate, minimal and non-responders], have been provided in Chapter 3.

7.3 Results

The results for this section are presented according to the: surgery demographics, differences at baseline between sub-groups, serial change in back pain, leg pain and function, and sub-group analyses of response.

7.3.1 Surgery demographics

A total of 125 DIAM devices were implanted in the 81 cases; 44 cases received a single implant, 30 cases, two implants, and seven cases, three implants. The most common primary level for the surgery was L4/5 (n=40) followed by L5/S1 (n=33), L3/4 (n=7), and L2/3 (n=1). The most frequently used device size, inserted at the primary (index) level, was 10mm (n=29), followed by 8mm (n=25) and 12mm (n=24), with 14mm devices the least commonly employed by the surgeon (n=3). The DIAM was implanted in two cases in isolation, as an augmentation to a single decompressive technique in 37 cases, and as an augmentation to more than one decompression technique in 42 cases. There were 13 (of 81) surgical failures having undergone repeat surgery at the index level during their 2-year postoperative course (further elaborated in Appendix XI). Case numbers per surgery-related category have been presented in Table 7.2.

7.3.2 Baseline sub-group differences

When baseline values for back and leg pain (determined using VAS) were assessed in terms of differences between demographic details or study categorisations, differences were shown between subgroups (Figure 7.1.1). Cases that received three DIAMs (n=7) had significantly higher mean (SD) back pain [64.7% (15.3%)] than cases receiving a single implant [n=44; 44.5% (23.3%)]. Subjects diagnosed with foraminal stenosis (FS; n=42) had higher mean baseline leg pain [55.5% (25.7%)] than subjects with each of the other diagnoses: central canal stenosis [CS; n=6; 20.7% (35.9%); $p<0.01$]; facet joint pain syndrome [FJPS; n=10; 34.3% (32.0%); $p<0.05$]; and degenerative spondylolisthesis [DS; n=23; 38.8% (28.1%); $p<0.05$]. Subjects that received more than one decompression procedure in addition to their DIAM (n=42) had more leg pain [51.6% (27.3%); $p<0.05$] than the two cases for which the implant was used in isolation [10.0% (14.1%); $p<0.05$], but were no different compared to cases receiving a single decompressive technique in addition to their implant [n=37; 41.0% (31.0%)].

As shown in Figure 7.1, when back and leg pain were triaged by anatomical categorisation [disc (>50% involvement), ‘disc’; facet (>50%), ‘facet’; mixed facet = disc (50% each), ‘mixed’] no differences between baseline levels of back and leg pain were detected. However, when a dicotomous comparison [disc (>50%); facet (≥50%)] was applied, back pain tended to be higher (but not significant) in predominant disc pathologies [52.4% (24.3%)] than those involving the facet joint [42.6% (24.2%); $p=0.08$], while leg pain also tended to be higher (but not significant) at baseline in disc cases [51.1% (26.5%)] compared to facet cases [38.7% (32.4%); $p=0.06$] (data not shown).

Table 7.2: Subject numbers according to: number of DIAMs implanted, index (primary) segment of surgery, DIAM size (implanted at the index level), the surgical procedure accompanying DIAM implantation, and the relationship between preoperative back and leg pains.

Category	Sub-categories	Females	Males	Total
# DIAMs	1	19	25	44
	2	14	16	30
	3	4	3	7
Primary Segment	L2/3	1	0	1
	L3/4	3	4	7
	L4/5	21	19	40
	L5/S1	12	21	33
DIAM Size (mm)	8	13	12	25
	10	9	20	29
	12	14	10	24
	14	1	2	3
Surgical Procedure	0	1	1	2
	1	22	15	37
	>1	14	28	42
BackP-LegP (baseline)	Equal	7	10	17
	BP>LP	17	15	32
	LP>BP	13	19	32

#DIAMs=Number of DIAMs implanted per case; Primary segment=spinal segmental level where the primary DIAM surgery was intended; DIAM size=the size of the DIAM employed at the primary segment; Surgical procedure=number of decompression techniques employed in addition to inserting a DIAM [0=DIAM in isolation, 1=a single decompressive procedure, >1=more than 1 additional decompressive procedure]; BackP-LegP (baseline)=the difference between patient-reported back pain and leg pain at the preoperative baseline [Equal=no difference, BP>LP=back pain worse than leg pain, LP>BP=leg pain worse than back pain].

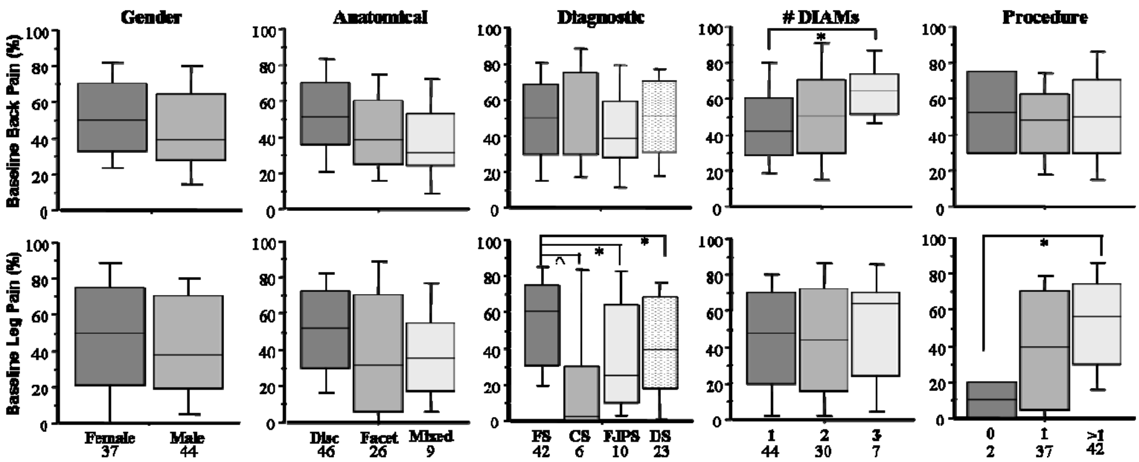


Figure 7.1: Box-plots presenting differences in preoperative back and leg pain between genders, anatomical classification [disc, facet, mixed], diagnostic categorisation [foraminal stenosis (FS), central canal stenosis (CS), facet joint pain syndrome (FJPS), degenerative spondylolisthesis (DS)], the number of implanted DIAMs, and additional decompressive procedures [0=DIAM in isolation, 1=a single decompression procedure, >1=more than 1 additional decompressive procedure]. Case numbers for each category are indicated (x-axis) *p<0.05, ^p<0.01 significant.

Baseline back pain (VAS), leg pain (VAS) and function (ODI) were examined in terms of subject's absolute [12m-B] and normalised for baseline [(12m-B)/B] response to the surgery at 12 months. Each variable was significantly worse in moderate responders when absolute response (at 12 months after surgery) was compared to minimal and non-responders, while no differences were noted in terms of normalised to baseline response (Figure 7.2).

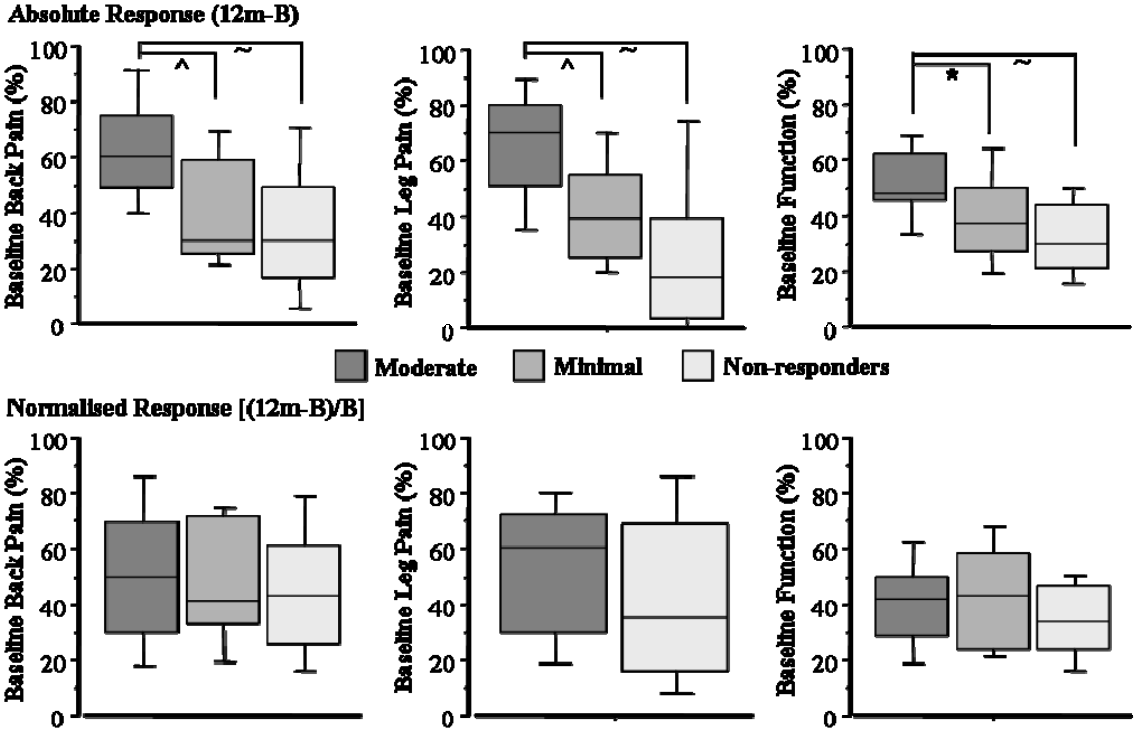


Figure 7.2: Baseline back pain, leg pain and function split to indicate differences between moderate, minimal and non-responders according to absolute [12m-B] and normalised for baseline [(12m-B)/B] response at 12 months postoperatively. Baseline pain and function are equitable when considered according to normalised response. Significant differences between groups are indicated: *p<0.05, ^p<0.01, ~p<0.001

7.3.3 Serial changes for the group in patient-reported outcomes

The mean values for back pain, leg pain and function, as reported by 81 cases after lumbar surgery augmented with the DIAM along their two year postoperative course, are presented in Table 7.3 and illustrated in Figure 7.3. Significant improvement for back and leg pain (VAS) and back-specific function (ODI) was confirmed at all time-points after surgery compared to baseline values. The greatest improvement for mean back pain was achieved at six weeks (by 30.5%; p<0.0001), which was maintained to 3 months, with gradual deterioration (which was significant between 6 weeks and both 18 and 24 months) to two years after surgery, despite remaining significantly better than preoperatively (improved by 20.4%; p<0.0001). The greatest improvement for mean leg pain was also achieved at six weeks (by 29.3%; p<0.0001), which gradually deteriorated (significantly between 6 weeks and 18 months) to two years after surgery, despite remaining significantly better than preoperatively (improved by 20.3%; p<0.0001). The greatest improvement for mean function occurred at 3 months postoperatively (by 18.7%; p<0.0001), with gradual deterioration thereafter to two years after surgery, despite remaining significantly better (by 15.1%; p<0.0001) than at preoperative levels.

Table 7.3: Mean (SD) [SEM] values for back pain, leg pain and function as reported by 81 subjects at several time-points along a two year postoperative course after lumbar surgery augmented with the DIAM. All variables were significantly improved at each consecutive time-point compared to baseline. Significant differences between each postoperative time-point and baseline are indicated.

Mean (SD) [SEM]	Back Pain (VAS%)	Leg Pain (VAS%)	Function (ODI%)
Baseline	48.1 (24.6) [2.7]	45.8 (29.6) [3.3]	39.0 (16.2) [1.8]
6 weeks	17.6 (20.9) [2.3][4]	16.5 (23.4) [2.6][4]	23.6 (18.6) [2.1][4]
3 months	17.7 (23.7) [2.6][4]	17.2 (24.2) [2.7][4]	20.3 (18.2) [2.0][4]
6 months	22.7 (23.6) [2.6][4]	18.6 (25.2) [2.8][4]	22.3 (19.9) [2.2][4]
12 months	21.4 (25.2) [2.8][4]	20.8 (26.4) [2.9][4]	22.3 (19.5) [2.2][4]
18 months	28.3 (30.1) [3.3][4]	28.1 (30.2) [3.4][4]	23.9 (19.7) [2.2][4]
24 months	27.7 (29.5) [3.3][4]	25.5 (30.6) [3.4][4]	23.9 (20.8) [2.3][4]

[4]p<0.0001 Significant difference compared to baseline values

Serial results for patient-reported satisfaction and medication use postoperatively are presented in Figures 7.4 & 7.5, respectively. At 12 months after surgery, 57 (of 81) cases were more satisfied than preoperatively, with one subject with improved satisfaction still reporting being dissatisfied on the 5-level Likert scale (refer to Figure 7.4). At 24 months after surgery, 56 (of 81) cases were more satisfied than preoperatively, with eight of those subjects reporting being dissatisfied. Forty-seven subjects (at each time-point) reported being either satisfied or very satisfied with their symptoms at 12 and 24 months postoperatively.

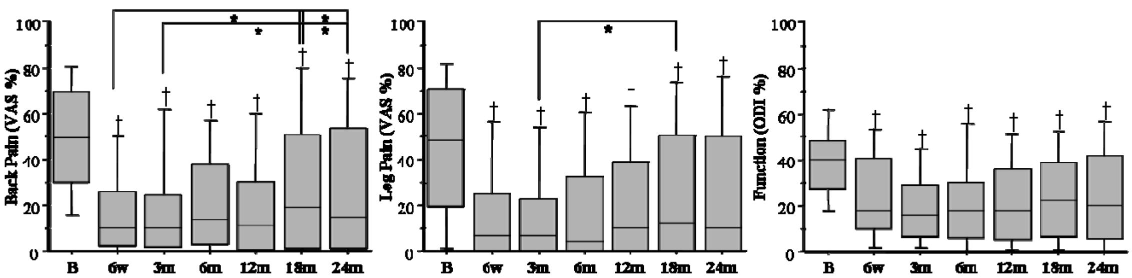


Figure 7.3: Box-plots presenting serial change over two years for back pain, leg pain and function in a cohort of 81 cases after DIAM-augmented surgery used in treatment of their degenerative lumbar spinal disease. Significant differences are indicated between time-points (*p<0.05). All postoperative time-points compared to baseline for each of back pain, leg pain and function, were significant (†p<0.0001).

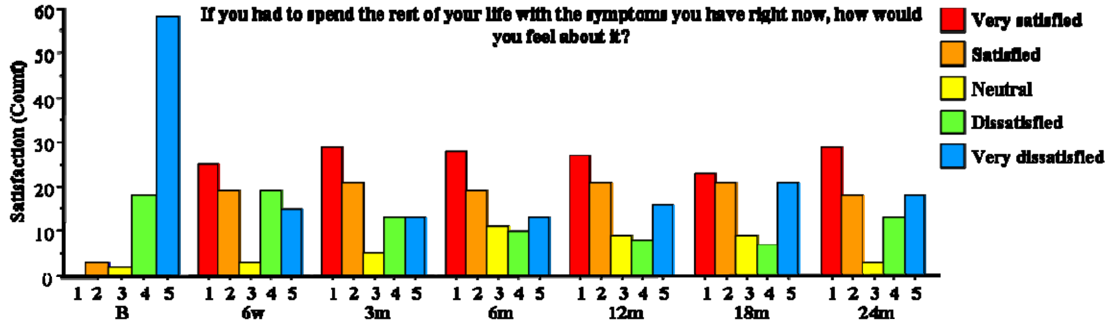


Figure 7.4: Histogram revealing patient-reported satisfaction over the two year period of observation for 81 cases after surgery involving DIAM.

Excluding the five cases that were not using medication before surgery or at one or two years postoperatively, at 12 months after surgery, 43 (of 76) cases were using fewer pain medications than preoperatively, with four of those cases still taking daily medication. Thirty-four cases were not taking medication, or only once a week, at 12 months postoperatively.

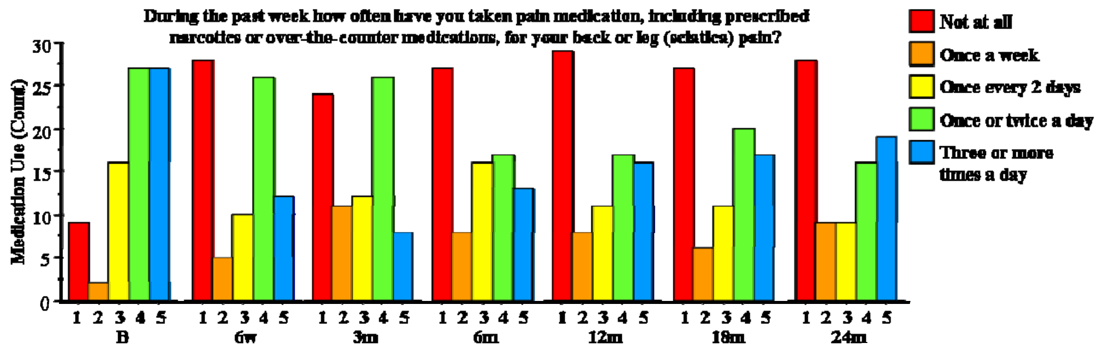


Figure 7.5: Histogram revealing patient-reported medication use over the two year period of observation for 81 cases after surgery involving DIAM.

At 24 months after surgery, 36 (of 76) cases were using fewer medications than preoperatively, with three of those cases still reporting taking daily medication. At two years postoperatively, 37 cases were either not taking pain medication or only once a week.

7.3.4 Sub-groups analyses: change in pain and function at one and two years postoperatively

When the patient cohort was analysed according to sub-groups, mixed results were found, as demonstrated in Table 7.4. No difference in change at one or two years after surgery compared to preoperative baseline were detected between genders, age under or over 50 years, anatomical diagnoses and the quantity of DIAMs implanted. Significant differences were noted according to clinical diagnoses, DIAM size, associated decompressive procedure(s) and the predominance of either back or leg pain at baseline; these are detailed below.

Diagnosis: Cases categorised with foraminal stenosis (FS; n=43) had significantly better mean (SD) improvement in back pain at 12 months [32.2% (27.4%)] than cases with the diagnosis of degenerative spondylolisthesis [DS; n=22; 14.9% (28.1); p<0.05]. No other differences between changes in back pain at one year were noted. Additionally, FS cases had superior improvement in leg pain at 12 months [39.8% (31.2)] compared to central canal stenosis [CS; n=6; worsened by 9.5% (21.4); p<0.001], facet joint pain syndrome [FJPS; n=10; 9.5% (30.9%); p<0.01], and DS cases [n=22; 12.3% (34.5); p<0.01]. In terms of change in back pain at the two year postoperative time-point, cases with DS had significantly poorer improvement [2.7% (30.4)] compared to the cases with FS [28.7% (29.1); p<0.05]. Leg pain improved significantly more in cases with FS [37.7% (29.2)] than all other diagnoses [CS, 5.5% (19.2), p<0.05; FJPS, 2.6% (33.0), p<0.01; DS, -1.6% (40.2), p<0.001]. Improvements in function at two years were greater in those with FS [22.3% (20.9)] than those with DS [3.1% (20.4); p<0.0001].

DIAM size: The three cases receiving a 14mm DIAM had a mean improvement of 50% in back pain at 12 months (NS) and 77% improvement in leg pain, which was a significantly better (p<0.05) result than cases being implanted with the other device sizes (refer to Table 7.4). Although these (three) subjects had higher percentages of improvement in back and leg pain at two years after surgery, the difference compared to the other device sizes at the primary surgical level, was not statistically significant. Cases receiving a 10mm DIAM appeared to show the least improvement.

Procedure: Cases who received more than one adjunctive decompressive technique (n=42) had better improvement in back pain at 12 months [32.3% (29.0)] than those receiving a single decompression in addition to their DIAM [n=37; 19.4% (26.9); p<0.05]. Similarly, those receiving multiple decompressions had significantly better improvement in leg pain at 12 months [33.5% (33.4)] compared to cases receiving a single [16.1% (36.1)] or no decompression procedure [n=2; 10.0 (14.1); p<0.05]. In terms of change in pain at the two year postoperative time-point, cases receiving more than one decompression procedure had superior (moderate) improvement [30.3% (34.3)] than subjects receiving a single decompression technique in addition to their DIAM insertion [9.5% (38.1); p<0.05].

Difference between back pain and leg pain at baseline: In cases whose leg pain was worse at baseline compared to their back pain, a significantly better response for leg pain at 12 months (p<0.01) and 24 months (p<0.0001) was noted compared to subjects with more or equivalent back pain preoperatively.

Responder groups: Case numbers according to responder groups in terms of back pain, leg pain and function at the one and two year postoperative time-points are presented in Figure 7.6. Results indicate that a greater proportion of responders were evident at the 12 month postoperative time-point as compared with two years after surgery, where virtually 50% of cases were either a responder or non-responder.

Table 7.4: Mean (SD) change scores (%Δ) for back pain, leg pain, and function, at one and 2 years postoperatively compared to baseline, for 81 cases after surgery involving implantation of the DIAM. Results are presented according to sub-group categories. Significant differences between groups are indicated (p<0.05). Scores are presented as % improvement; negative values indicate worsening compared to baseline.

		1 year-Baseline (%Δ)			**2 years-Baseline (%Δ)**		
		Back	Leg	Function	Back	Leg	Function
Gender	Female	26.5 (28.8)	24.2 (34.1)	15.9 (19.3)	18.1 (30.4)	15.4 (37.0)	12.6 (18.6)
	Male	27.0 (28.8)	25.6 (36.5)	17.4 (23.9)	22.4 (34.1)	24.4 (36.9)	17.3 (24.7)
Age	<50yrs	27.4 (31.9)	30.1 (35.1)	17.2 (24.2)	21.0 (31.7)	23.3 (40.1)	15.1 (24.4)
	≥50yrs	26.3 (26.6)	21.6 (35.3)	16.4 (20.3)	20.1 (33.1)	18.3 (35.1)	15.2 (20.7)
Anatomy	Disc	28.4 (31.8)	32.6 (34.4)	19.0 (24.1)	23.4 (33.4)	27.2 (35.3)	17.1 (23.2)
	Facet	26.2 (26.1)	13.4 (35.6)	13.8 (18.9)	22.5 (27.8)	14.8 (32.2)	12.8 (19.5)
	Mixed	20.1 (16.8)	19.1 (31.7)	13.2 (17.4)	-0.7 (35.1)	0.8 (51.5)	11.9 (25.1)
Diagnosis	FS	32.2 (27.4)	39.8 (31.2)	22.4 (22.0)	28.7 (29.1)	37.7 (29.2)	22.3 (20.9)
	CS	25.5 (25.8)	-9.5 (21.4)[3]	11.7 (7.9)	24.8 (23.3)	5.5 (19.2)[1]	13.8 (5.9)
	FJPS	30.3 (32.6)	9.5 (30.9)[2]	16.2 (22.9)	21.3 (42.4)	2.6 (33.0)[2]	11.3 (26.5)
	DS	14.9 (28.1)[1]	12.3 (34.5)[2]	7.2 (20.8)	2.7 (30.4)[1]	-1.6 (40.2)[4]	3.1 (20.4)[4]
#DIAMs	1	24.1 (27.0)	27.0 (33.0)	16.9 (25.2)	20.0 (28.6)	25.0 (36.7)	16.3 (24.6)
	2	28.4 (32.3)	24.4 (40.1)	18.6 (17.1)	20.2 (37.5)	16.1 (37.5)	15.1 (19.7)
	3	36.4 (21.4)	14.4 (28.4)	7.3 (16.0)	24.1 (35.8)	9.0 (37.2)	7.7 (15.6)
Size (mm)	8	27.4 (28.9)	30.1 (27.6)	20.9 (19.1)	26.3 (32.4)	30.4 (26.9)	21.2 (19.8)
	10	20.3 (29.3)	16.4 (38.0)	11.8 (25.0)	15.7 (32.7)	13.4 (38.7)	10.3 (24.1)
	12	31.0 (27.7)	23.4 (35.5)	17.2 (20.7)	19.0 (30.5)	15.0 (41.3)	14.6 (20.9)
	14	50.0 (15.9)	77.7 (13.7)[1]	25.0 (16.6)	29.7 (51.7)	44.3 (47.8)	16.0 (29.1)
Procedure	None	48.5 (29.0)	10.0 (14.1)	27.0 (7.1)	50.0 (28.3)	10.0 (14.1)	27.0 (4.2)
	One	19.4 (26.9)	16.1 (36.1)	13.8 (22.1)	10.6 (29.1)	9.5 (38.1)	10.6 (21.6)
	>One	32.3 (29.0)[1]	33.5 (33.4)[1]	18.7 (21.9)	27.7 (33.1)	30.3 (34.3)[1]	18.5 (22.5)
BP-LP B	Equal	28.8 (26.3)	18.4 (24.1)	11.1 (20.8)	25.6 (26.5)	21.8 (23.1)	13.5 (19.3)
	BP>LP	27.4 (29.6)	8.2 (32.2)	15.8 (21.3)	19.1 (35.3)	0.8 (37.0)	12.8 (21.5)
	LP>BP	25.1 (29.6)	45.3 (33.6)[2]	20.5 (22.6)	19.1 (32.8)	38.9 (33.6)[4]	18.3 (24.3)

Anatomy=anatomical categorisation [Disc=>50% disc involvement; Facet=>50% facet involvement; Mixed=50:50% disc:facet]; FS=foraminal stenosis; CS=central canal stenosis; FJPS=facet joint pain syndrome; DS=degenerative spondylolisthesis; #DIAMs=number of levels implanted with a DIAM; Procedure=decompressive procedure in addition to DIAM insertion: None=DIAM alone, One=single adjunctive decompressive technique, >One=more than one adjunctive decompressive technique; BP-LP B=Back pain minus leg pain as reported by subjects at baseline [Equal=the same level of back and leg pain reported; BP>LP=back pain higher than leg pain, LP>BP=leg pain higher than back pain]. Significant differences are indicated and explained further in the related text in the preceding paragraphs: [1]p<0.05; [2]p<0.01; [3]p<0.001; [4]p<0.0001

Patient's self-reported satisfaction at one and two year time-points are compared with the degree of absolute response to the surgery for back pain, leg pain and function and case numbers according to each category are presented in Table 7.5. Results indicate that not all responders were satisfied with their symptoms at the time of completing the survey.

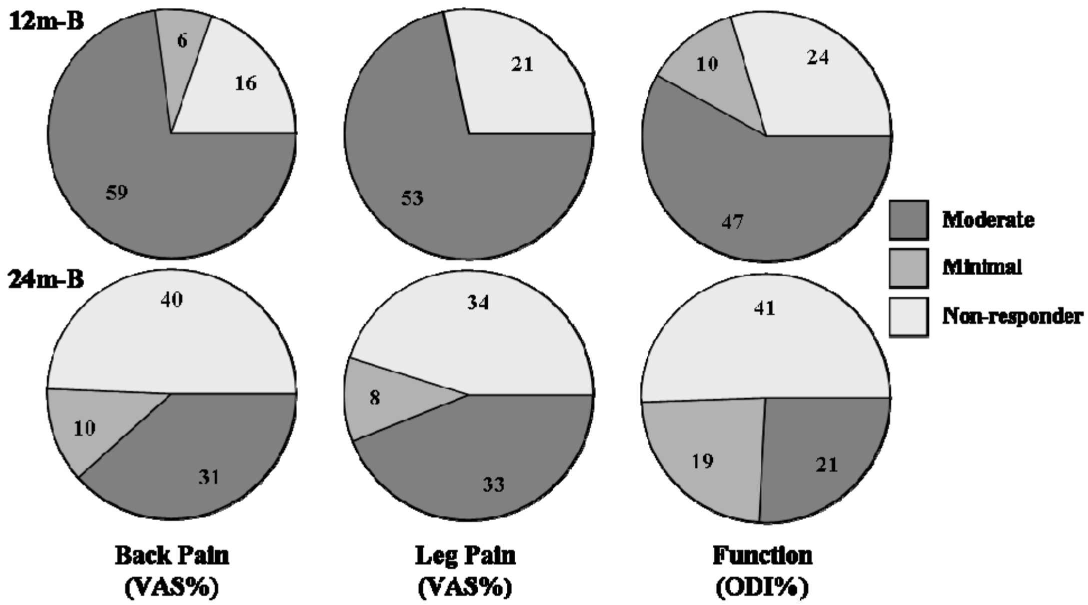


Figure 7.6: Pie-charts revealing the proportions of moderate, minimal and non-responders for change in back pain (left), leg pain (centre) and function (right) in 81 cases receiving lumbar surgery augmented with DIAM at 12 (top) and 24 months (bottom) postoperatively compared to baseline values.

Table 7.5: Case numbers according to level of satisfaction with current symptoms, and back pain, leg pain and functional response, at one and two years postoperatively in 81 subjects after lumbar surgery augmented with DIAM. Results indicate that not all responders to the surgery (according to recommended thresholds; Dworkin et al 2008 & Ostelo et al 2008) were satisfied with their current symptoms.

Satisfaction		**One year**			**Two years**		
		Back	Leg	Function	Back	Leg	Function
Very	R	26	22	25	21	22	26
Satisfied	NR	1	2	2	7	5	3
Satisfied	R	20	18	19	13	11	9
	NR	1	2	2	5	4	9
Neutral	R	7	4	5	2	0	0
	NR	2	4	9	1	3	3
Dissatisfied	R	6	4	4	4	5	3
	NR	2	3	4	9	8	10
Very	R	6	5	4	1	3	2
Dissatisfied	NR	10	10	12	17	14	16

R=Responders [back & leg pain ≥20%; function ≥15% improvement]; NR=Non-responders [back pain & leg pain <20%; function <15% improvement].

7.3.5 Sub-groups analyses: serial change

When serial change in back pain (Figure 7.7), leg pain (Figure 7.8) and function (Figure 7.9) over the two year postoperative course were split according to sub-groups, several differences between categories were revealed. Each will be reported separately below.

Gender: In terms of back pain, male cases (n=44) showed highly significant improvement (p<0.0001) compared to baseline at all time-points out the two years, while female cases (n=37) showed comparable improvement to 3 months but deteriorated from 6 through to 24 months, despite remaining better than baseline (p<0.05). In terms of leg pain, males showed highly significant improvement (p<0.0001) compared to baseline at all time-points out the two years, while females showed comparable improvement at 6 weeks postoperatively (p<0.0001) but deteriorated from 3 months (p<0.001) through to 12 months (p<0.01), such that by 18 months after surgery their leg pain had not improved compared to baseline. In terms of function, male subjects showed highly significant improvement (p<0.0001) compared to baseline at all time-points out the two years, while the improvement seen in female subjects was less significant than in males at 6 weeks (p<0.01) but comparable from 3 to 12 months (p<0.0001), thereafter deteriorating at 18 through to 24 months after surgery (p<0.01).

Anatomical: When serial change in the 81 prospective cases was split according to anatomical categorisation, back pain improvement was highly statistically significant (p<0.0001) to 3 months postoperatively for cases with predominant disc (n=46) and facet (n=26) pathologies.

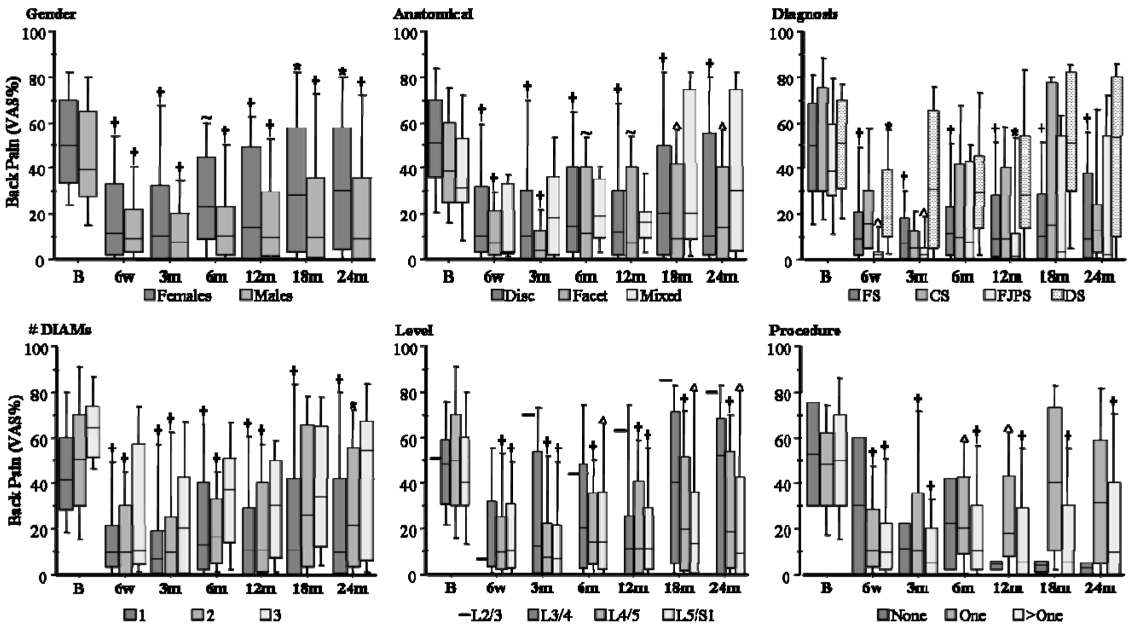


Figure 7.7: Box-plots revealing serial change in back pain for two years after DIAM-augmented lumbar surgery in 81 cases with lumbar spine disease. Data were split according to: gender [F37, M44]; anatomical categorisation [disc46, facet26, mixed9]; clinical diagnosis [FS43, CS6, FJPS10, DS22]; number of DIAMs implanted [1=44, 2=30, 3=7]; level of the primary implant [L2/3=1, L3/4=7, L4/5=40, L5/S1=33]; and accompanying decompression procedure [none=2, one=42, >one=37]. Statistically significant improvements between time-points (Scheffe) for each sub-group are indicated: *p<0.05, ^p<0.01, ~p<0.001, †p<0.0001.

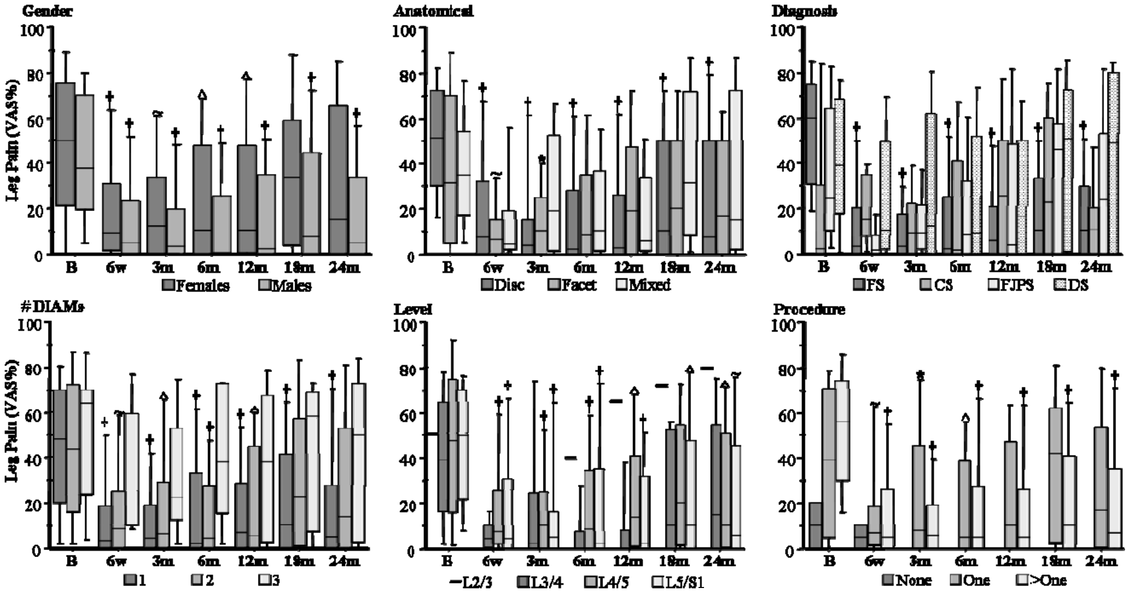


Figure 7.8: Box-plots revealing serial change in leg pain for two years after DIAM-augmented lumbar surgery in 81 cases with lumbar spine disease. Data were split according to: gender [F37, M44]; anatomical categorisation [disc46, facet26, mixed9]; clinical diagnosis [FS43, CS6, FJPS10, DS22]; number of DIAMs implanted [1=44, 2=30, 3=7]; level of the primary implant [L2/3=1, L3/4=7, L4/5=40, L5/S1=33]; and accompanying decompression procedure [none=2, one=42, >one=37]. Statistically significant improvements between time-points (Scheffe's) for each sub-group are indicated: *p<0.05, ^p<0.01, ~p<0.001, †p<0.0001.

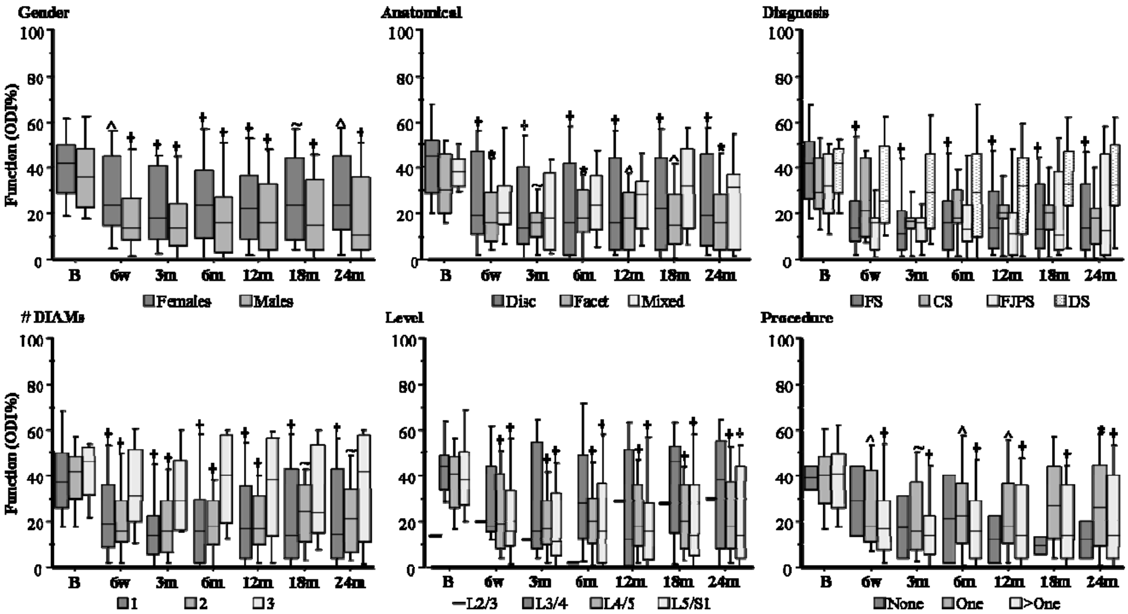


Figure 7.9: Box-plots revealing serial change in function for two years after DIAM-augmented lumbar surgery in 81 cases with lumbar spine disease. Data were split according to: gender [F37, M44]; anatomical categorisation [disc46, facet26, mixed9]; clinical diagnosis [FS43, CS6, FJPS10, DS22]; number of DIAMs implanted [1=44, 2=30, 3=7]; level of the primary implant [L2/3=1, L3/4=7, L4/5=40, L5/S1=33]; and accompanying decompression procedure [none=2, one=42, >one=37]. Statistically significant improvements between time-points (Scheffe's) for each sub-group are indicated: *p<0.05, ^p<0.01, ~p<0.001, †p<0.0001.

Beyond 3 months, disc cases continued to show highly significant improvement out to 24 months, while the facet cases gradually deteriorated despite remaining significantly better at two years compared to baseline ($p<0.01$). The nine cases with mixed spinal disease did not show improvement at any time compared to their preoperative status. In terms of leg pain, improvement was highly statistically significant ($p<0.0001$) throughout the two year course in cases with disc involvement. Facet cases showed initial significant improvement that was sustained to 3 months postoperatively ($p<05$) however deteriorated such that there was no difference compared to baseline from 6 months after surgery. Mixed cases did not show improvement at any time-point compared to their preoperative status. When function was considered, cases with predominant disc involvement showed highly significant improvements at all time-points ($p<0.0001$), while facet cases had improved at each time-point compared to baseline, yet not as convincingly as for discs. Mixed cases did not show improved function at any time-point compared to baseline.

Diagnosis: When serial change in the 81 prospective cases was split according to clinical diagnosis, back pain improvement was highly statistically significant ($p<0.0001$) at all time-points to two years in the cases with foraminal stenosis (FS; $n=43$; $p<0.0001$). Cases with facet joint pain syndrome ($n=10$) showed significant, but less statistically convincing improvement in back pain to one year postoperatively ($p<0.05$), while those with degenerative spondylolisthesis ($n=22$) had improved by 6 weeks ($p<0.05$) but not thereafter. The six cases diagnosed with central canal stenosis did not show any improved back pain. In terms of leg pain and function, only cases with FS showed improvement compared to baseline, which was highly significant at all postoperative time-points ($p<0.0001$).

Number of DIAMs: When serial change in the 81 prospective cases was split according to the number of DIAMs implanted per case, back pain improvement was highly statistically significant ($p<0.0001$) at all time-points to two years in the cases receiving a single device ($n=44$). Cases receiving two devices ($n=30$) showed highly significant improvement out to one year, with reduced significance at two years ($p<0.05$). Cases being implanted with three devices ($n=7$) showed no improvement in back pain compared to baseline values. In terms of leg pain, highly statistically significant ($p<0.0001$) improvement at all time-points to two years was shown in the cases receiving a single device. Cases receiving two devices showed significant, but less statistically convincing improvement to one year postoperatively ($p<0.01$), while cases being implanted with three devices ($n=7$) showed no improvement in leg pain compared to baseline values. In relation to function, cases receiving single and double level DIAMs improved significantly at all time-points out to two years, compared with baseline.

Level: When serial change in the 81 prospective cases was split according to the level of the primary implant, back pain improvement was highly statistically significant ($p<0.0001$) at all time-points to one year when the DIAM was implanted at L4/5 (n=40) or L5/S1 (n=33). L4/5 cases showed statistically better improvement after the first year however both groups had improved back pain at two years after surgery. In terms of leg pain, highly statistically significant ($p<0.0001$) improvement occurred to 6 months after surgery in the L4/5 and L5/S1 cases, but had slightly deteriorated for both by two years postoperatively. In relation to function, all L4/5 and L5/S1 cases showed highly significant improvements at all time-points compared to baseline ($p<0.0001$). Improvements seen in the L3/4 cases (n=7) for back pain, leg pain and function did not reach statistical significance at any time-point. Only one cases had the primary surgery at L2/3, with the trend for that case showing gradual deterioration from 6 weeks postoperatively.

Procedure: When serial change in the 81 prospective cases was split according to the number of decompression procedures employed in individual's surgeries, back pain improvement was highly statistically significant ($p<0.0001$) at all time-points to two years in the cases receiving more than one decompression technique during surgery (n=42). Less statistically convincing improvement in back pain was shown out to one year in cases for whom the DIAM was employed to augment a single decompression technique (n=37). The two cases that had the DIAM implanted in isolation had clinically important (≥30%) improvement in their back pain but statistical significance could not be analysed using Scheffe's post hoc test. In terms of leg pain, highly statistically significant ($p<0.0001$) improvement occurred throughout the two year period in cases receiving more than one decompression technique, however cases receiving only a single decompression procedure only improved out to 6 months after surgery and then returned to preoperative values. In relation to function, highly significant improvement ($p<0.0001$) was shown for the multiple decompression cases at each time-point compared to baseline throughout the two year observation period. Single decompression cases showed significant improvements to 12 months after surgery, which deteriorated and were then no better than baseline values by 18 months postoperatively, but continued to show a statistically significant improvement, although not of clinical significance, at two years compared to baseline.

Diagnosis & Anatomical categories combined: When serial change in the 81 prospective cases was split twice, first according to clinical diagnosis, and second according to anatomical categorisation, back pain and leg pain showed variable improvements dependent on sub-group (Figure 7.10). Improvement in back pain was highly statistically significant ($p<0.0001$) at all time-points to two years in the cases with foraminal stenosis and disc disease (FS&Disc; n=28; $p<0.0001$). FS and facet disease cases [FS&Facet; n=11] showed early improvement in terms of back pain to 3 months after surgery ($p<0.05$).

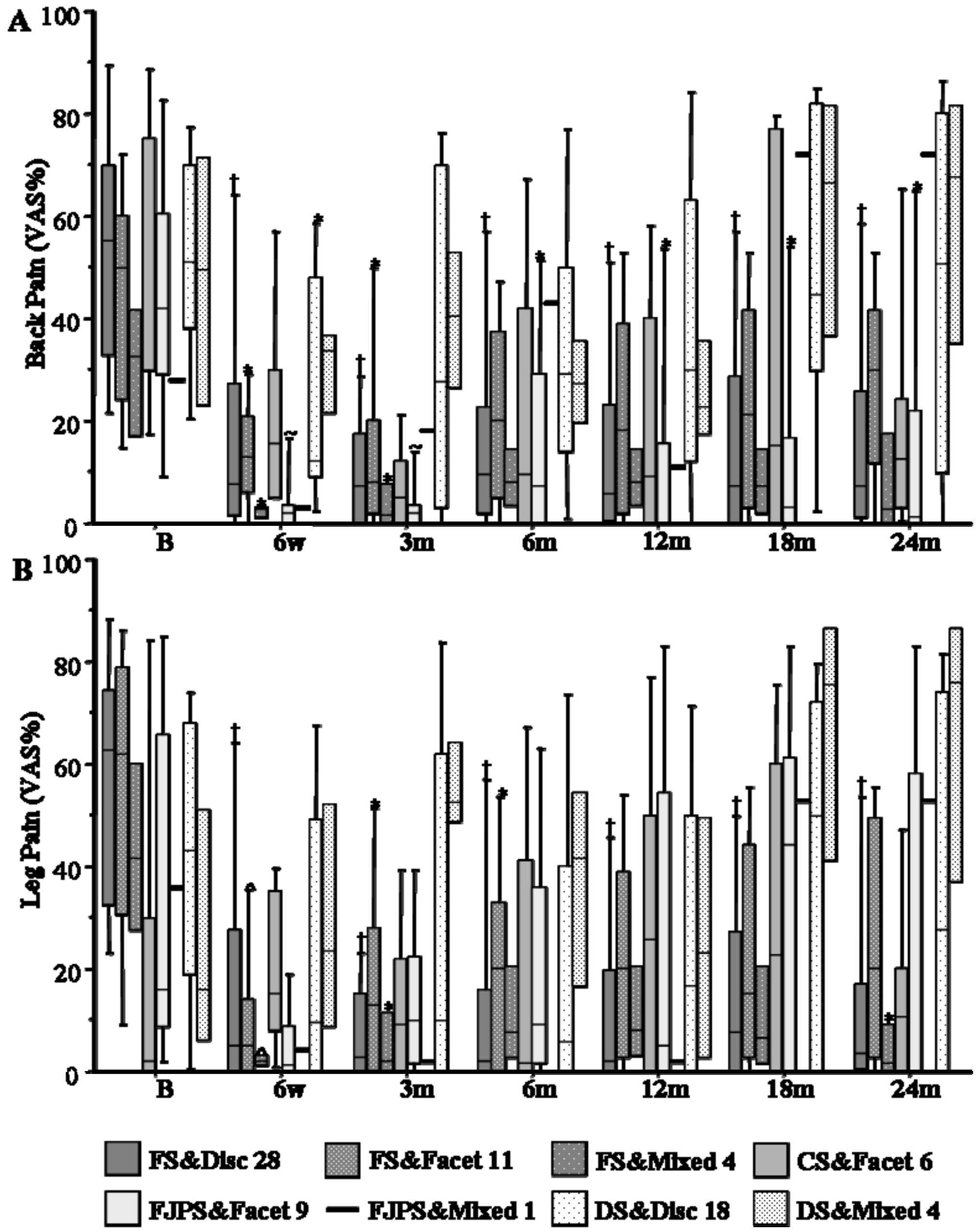


Figure 7.10: Box-plots revealing serial change in back (A) and leg (B) pain for two years after DIAM-augmented lumbar surgery in 81 cases with lumbar spine disease that were split according to clinical diagnosis and anatomical categorisation [FS&Disc 28, FS&Facet 11; FS&Mixed 4; CS&Facet 6, FJPS&Facet 9, FJPS&Mixed 1; DS&Disc 18; and DS&Mixed 4]. Statistically significant improvements between time-points (Scheffe's) for each 2-part sub-group are indicated: *$p<0.05$, ^$p<0.01$, ~$p<0.001$, †$p<0.0001$.

Cases with facet joint pain syndrome (who all had facet disease) (n=9) showed significant, but less statistically convincing improvement, at all time-points to two years postoperatively ($p<0.05$). Cases of degenerative spondylolisthesis and disc disease (n=18) had improved by 6 weeks ($p<0.05$) but not thereafter. All six cases diagnosed with central canal stenosis had predominant facet disease and did not show any improved back pain.

Improvement in back pain was highly statistically significant ($p<0.0001$) at all time-points to two years in the cases with foraminal stenosis and disc disease (FS&Disc; n=28; p<0.0001). FS and facet disease cases [FS&Facet; n=11] showed early improvement in terms of back pain to 3 months after surgery (p<0.05). Cases with facet joint pain syndrome (who all had facet disease) (n=9) showed significant, but less statistically convincing improvement, at all time-points to two years postoperatively (p<0.05). Cases of degenerative spondylolisthesis and disc disease (n=18) had improved by 6 weeks (p<0.05) but not thereafter. All six cases diagnosed with central canal stenosis had predominant facet disease and did not show any improved back pain.

Additionally, the cases with DS and mixed segment disease did not have improved back pain over the two year course. In terms of leg pain, cases with FS&Disc showed highly significant improvement compared to baseline at all time-points to two years (p<0.0001).

Other FS cases (accompanying predominant facet and mixed segment disease) showed improvement that was not statistically significant beyond 6 months postoperatively (p<0.05). No other sub-groupings had improved leg pain at any time-point over the two year period of observation.

7.4 Discussion

7.4.1 Clinical improvement: MID recommendations

Several investigations have reported improvements after lumbar surgery involving the DIAM (as revealed in Table 4.1), yet no investigators reference changes in pain and function, to expert recommendations considered for clinically important and meaningful differences (MID) in low back pain pathologies (Dworkin et al. 2008; Ostelo et al. 2008). Hypothesis 1 for this thesis investigation predicted that improvements in pain and function after DIAM-augmented surgery would exceed MID thresholds, in a time-dependent nature. Indeed, results showed highly statistically significant improvement in back pain, leg pain and function, at all time-points out to two years in the 81 prospective cases that received lumbar surgery involving the DIAM (Table 7.3 and Figure 7.3). Back pain (VAS) improved by a clinically important difference (>30%) at six weeks postoperatively, which was maintained to 3 months after surgery, but then showed gradual deterioration to two years when the improvement was only at a minimal clinically significant level (>20%). Leg pain (VAS) did not quite achieve a clinically important improvement at any time-point after surgery, but was best at six weeks postoperatively (improved by 29.3%), which then gradually deteriorated to two years when the improvement was only at a minimally clinically significant level (20.3%). Similarly, patient-reported function (ODI) had improved best by 3 months postoperatively (18.7%) but only to a minimally clinically significant level, deteriorating marginally to continue to be minimally better at two years after surgery (15.1%). Therefore, although Hypothesis 1 can be confirmed, mean improvement at two years was only minimally clinically significant, and potentially not important or meaningful to patients (Dworkin et al. 2008; Ostelo et al. 2008). In terms of time-dependent response to surgery, both back and leg pain had improved best at 6 weeks, while function showed best improvement at 3 months postoperatively. It may therefore be reasoned that 3 months represents a critical time-point in patient response after DIAM-augmented surgery, with potential for gradual deterioration in back pain, leg pain and function beyond that time-point out to two years.

7.4.2 Facet versus disc response

Table 7.4 shows superior results in subsets of cases at one and two years after surgery, particularly in relation to diagnostic categories. The retrospective audit outlined in Chapter 4, indicated superior response to DIAM-augmented surgery in cases whose pathology included involvement of the facet joints (Crawford et al. 2009a). Consequently, Hypothesis 2 predicted that cases with predominant facet disease, from the prospective phase of the study, would have superior responses compared to either the predominant disc cases, or those with equal disc and facet contributions (mixed) to their pathology. This result was not borne out by the findings in the current chapter, where in contrast, cases categorised with predominant disc pathology, showed superior improvements in back pain (Figure 7.7), leg pain (Figure 7.8) and function (Figure 7.9). Additionally, cases with foraminal stenosis and disc disease, responded better than those with foraminal stenosis and facet degeneration (Figure 7.10). Therefore, Hypothesis 2 was rejected.

In terms of MID recommendations, distinction between primary disc and facet cases was seen by their response to surgery in terms of leg pain (Table 7.4). At 12 and 24 months, disc cases showed moderate and minimal clinical improvement, respectively, while facet cases were not responsive to the surgery in terms of leg pain. Although significant early improvement in LP was noted in facet cases, the lack of statistically significant improvement at one and two years after surgery, probably related to variability in their baseline values (Figure 7.8).

It is interesting that the anatomically-based conclusions from the retrospective audit of 39 cases differed from the findings based on the prospective series of 81 cases. This contrasting result may have been due to employing different outcome instruments between the studies, and the methodological processes of surgeon-based patient classifications. Phase I of the study required the surgeon to categorise subjects retrospectively and generally after their two year postoperative period, while all surgeon categorisations for Phase II were done a priori. Although the surgeon categorisations were confirmed by the author based on case-note audits for both patient cohorts, the potential for bias existed. The smaller samples of facet compared to disc cases for Phases I and II may have influenced the results [Retrospective: disc=25, facet=14;

Prospective: disc=46, facet=26, mixed=9]. Additionally, the surgeon's clinical experience in using the DIAM may have had an influence given the time-period between the data collection for the two studies. Consequently, emphasis was placed on the results of the prospective arm of the study. The results presented in Chapter 4 and the present chapter indicate differences in response to surgery between anatomically-based categories, consequently further investigation that references the fundamental anatomical and pathological basis to patient's presentation appears necessary. It might also be argued that pathology with primary disc involvement represents a more discreet problem of soft tissue origin, while facet dysfunction indicates a bony and potentially more extensive issue.

7.4.3 Defining clinical indications

A primary objective in this thesis investigation was to attempt to better define clinical indications that might be best suited to surgery involving the DIAM. Consequently, outlining prognostic determinants of responders was an important aspect of the sub-group analyses performed in the study. No other authors have compared response to the surgery according to sub-sets of cases, and therefore the results of this investigation provide original insight into the magnitude of response within a relatively heterogeneous cohort of patients.

Baseline determinants of response: Unsurprisingly, when baseline values for back pain, leg pain and function were considered according to the absolute response at one year, patients with the highest preoperative levels of discomfort or dysfunction were those that had the best response to surgery. However, when response was normalised for baseline values, no significant differences in baseline values for each were detected. This result is discussed later in the chapter.

In cases whose leg pain was worse at baseline compared to their back pain, a significantly better absolute response for leg pain at one and two years postoperatively occurred compared to subjects with more or equivalent back pain preoperatively. Whether a subject was aged either under or over 50 years did not impact on their response to the intervention in this cohort of 81 cases where being aged over 50 years was more common (Table 7.1).

Sub-group analysis of serial response: When split according to the various sub-groups used in the study, several case categories showed superior results to their counterparts. These will be considered separately with reference to data presented in Table 7.4 and Figures 7.7-9.

Gender: On gender-based comparison, female patients complained of more (although not significant) preoperative back and leg pain than males. Male cases showed superior and more sustained improvement than women (NS), who tended to have deteriorating back pain, leg pain and function, after the first postoperative year. This may suggest that men benefitted more from lumbar surgery augmented with DIAM, particularly in the longer term.

Anatomical: As discussed previously, cases with predominant disc involvement had a better although not significant response to surgery at two years postoperatively that cases with primary facet or a mixed pattern of segment disease.

Diagnosis: Diagnosis-based comparisons revealed that cases categorised with foraminal stenosis had the best response to the surgery in terms of back pain, leg pain and function, compared in particular, to cases with central canal stenosis and degenerative spondylolisthesis, whose self-reported outcomes did not change after DIAM-augmented surgery. Distinction between categories was most noted for response in terms of leg pain where FS cases showed meaningful improvement ($<30\%$) at both one and two years ($p<0.0001$). Subjects with facet joint pain syndrome showed significantly improved back pain (although not as good as in FS cases), but not in terms of their leg pain or function. These results indicate that cases with foraminal stenosis respond best to DIAM-augmented lumbar surgery, followed by those with FJPS. Subjects with central canal stenosis or degenerative spondylolisthesis did not improve after DIAM-augmented surgery compared to their preoperative status.

Number of DIAMs implanted: When compared according to the number of DIAMs implanted at surgery for each case, subjects receiving a single implant responded better (although not significantly different) over the 2 year term for back pain, leg pain, and function, than cases receiving two implants. Subjects implanted with two devices had significant improvement out to one year postoperatively, which was not sustained at two years. Cases receiving three DIAMs did not respond to the surgery when change in pain and function from baseline was considered.

Segmental level: In terms of the level of the primary implanted device, cases receiving their DIAM at either L4/5 or L5/S1 showed improvement postoperatively, which was better at L4/5 in terms of back pain, but comparable (between L4/5 and L5/S1 surgeries) for leg pain and function. This result indicates that cases with segment disease in the lowest two lumbar segments represent those most likely to improve from the surgery. Although not overly useful given the majority of cases had their primary dysfunction at these two levels, the result is in agreement with incidence data for degenerative spinal disease of the lumbar region. It may be that insertion of the DIAM is best achieved at these levels where surgical access may be easier due to relatively larger disc heights in the lumbosacral region (Bernhardt and Bridwell 1989).

Adjunctive surgical procedure(s): Adjunctive surgical procedure-based comparisons showed that subjects receiving multiple decompressive techniques during surgery, were the only cases to show sustained improvements in back pain, leg pain and function, at each time-point out to two years postoperatively. Subjects whose surgery included a single decompression technique in addition to DIAM insertion, showed improvements in back and leg pain, but only within the first postoperative year. There were only two patients who had the DIAM inserted in isolation and although they showed a trend for mean improvement in outcomes, no conclusions could be made. These results suggest that cases receiving more extensive decompression surgery at the time of DIAM implantation had a more favourable response postoperatively.

The results presented in Figure 7.1, support the reasoning behind sub-classifying patients with lumbar spinal stenosis, wherein cases diagnosed with foraminal stenosis had significantly more leg pain preoperatively than those diagnosed with central canal stenosis. Additionally, cases with FS had higher leg pain preoperatively, than those with facet joint pain syndrome and degenerative spondylolisthesis. Although the result itself is not surprising given leg pain would be anticipated due to neural tissue irritation secondary to a stenotic foramen, the potential for a different response to the surgery existed across diagnostic groups when their baseline symptoms differed; this was borne out in the serial sub-group analyses (Figures 7.7-9).

Cases with FS had superior improvement in patient-reported HRQoL compared to each of the other diagnostic categories, including central canal stenosis. Although this study did not ask patients to differentiate between the presence of unilateral or bilateral back or leg pain symptoms, it is reasonable to assume that cases with unilateral foraminal stenosis would have associated ipsilateral leg pain based on the innervation (Bogduk et al. 1982; Bogduk 1983; Groen et al. 1990). The baseline values for leg pain being higher in those with FS compared to CS would support this speculation. It might also be argued that in cases presenting with symptoms predominant on one side, would steer the surgeon to a surgical approach to that side in order to access (and excise) the nociceptively-sensitised tissues. The side of approach to the surgery was not documented by the surgeon for the present series of patients, but one might argue this decision would be based on preference. As occurs typically to accompany DIAM surgery, decompression is also performed, which for unilateral foraminal stenosis would treat the affected side, but potentially not so for cases of central canal stenosis where a pathology affecting both sides of the canal would be anticipated, and therefore a more extensive surgical undertaking. It might be argued that FS represents a more discreet pathology with an easier (unilateral) surgical access.

The lack of clarity regarding the extent of decompression used highlights a potential limitation to research examining decompression surgeries (including the insertion of an ISP) where several adjunctive procedures might be used with the potential for decompression, yet they’re all grouped singularly as ‘decompression’. This approach for classifying decompression surgery is supported by a recent paper that promotes the use of an index in categorising the invasiveness of lumbar surgery (Mirza et al. 2008). However, for minimally invasive surgeries, where the reduced extent of the intervention is a purported benefit, documenting what specific tissues are excised or affected by the surgery, may be of importance in understanding response. In their study of 187 patients receiving discectomy in treatment of sciatica, Carragee et al (2003) reported that intraoperative findings, like the degree of anular competence and the type of herniation, were more predictive of postoperative outcome, than demographic, socioeconomic or clinical variables. Their paper concluded that subsets of herniated discs were likely to represent different clinical syndromes (Carragee et al. 2003). This elaborated earlier findings of Knop-Jergas et al (1996) who reported that the anatomical position of a HNP predicted postoperative discectomy outcomes. They showed that poorer clinical outcome were statistically significant in patients with central herniations and with multiregional protrusions (Knop-Jergas et al. 1996). The impact of this in relation to the extent of the associated surgery is therefore implied.

The present investigation showed that cases receiving more than one documented decompression technique, responded more favourably than those receiving only a single procedure in addition to their DIAM insertion. The classification regarding decompression procedure used in this study was based on the surgeon's operative report which generally listed any techniques used. Perhaps a more suitable method would be to reference an index or grade that relates to the location and quantity of removed tissues, bone or otherwise. Variable types of laminotomies for HNP surgeries are outlined by Bauer et al (1993) (Figure 2.x). A similar protocol could be adopted for research following decompression or minimally invasive surgical procedures, particularly in the case of national or international spinal registries where cross-sectional comparisons of data are intended (Melloh et al. 2008; Kleinstuck et al. 2009; Zweig et al. 2009). Whether surgeons would comply with this record-keeping initiative is not known, however it appears necessary to standardise the recording of intraoperative findings and procedures in order to better delineate clinical indications. The final aim should be to identify relevant pathological features preoperatively with imaging, to mitigate surgeries with limited prognostic success.

As indicated, cases in this study that received a more extensive surgical decompression appeared to have superior improvement over the longer term. This result highlights a limitation to the present study where the postoperative outcomes could not be isolated to the influence of the device itself. Only two cases were implanted with the DIAM alone and therefore were not an adequate comparator for the effect of the DIAM in isolation. Similarly, the lack of a randomised decompression-alone control group, made the distinction of effect of the surgery difficult to appreciate. However, an adjunctive investigation was undertaken to contrast the effect of surgery over a postoperative year, in two cohorts of subjects from the same surgeon, who received either decompression surgery alone, or augmented with a DIAM, in treatment of their HNP (Appendix X). Although several limitations with the comparative study made conclusions difficult, superior results were seen in the cohort of cases who received decompression alone. The lack of studies comparing DIAM surgery to its decompression alternatives is a glaring omission in the literature that warrants attention to appropriately validate the clinical use of the device.

Several outcomes followed in this study showed significant improvement out to one year postoperatively, but with a diminishing effect beyond that to two years. This result highlights the importance of structuring prospective observational longitudinal studies with an extended observation period, wherein two years might also be considered relatively short term (Amundsen et al. 2000).

Differences between baseline levels of back pain, leg pain and function when split according to their absolute response at 12 months postoperatively, as opposed to no significant difference at baseline in terms of their normalised for baseline response to the surgery are shown in Figure 7.2. The interpretation of these results suggests that subjects, who went into surgery reporting the highest levels of pain or dysfunction, were more likely to have a superior improvement in symptoms after surgery. This result is intuitively reasonable however it highlights a potential weakness in reporting absolute change in patient-reported outcomes. By this measure, improvement, even in patients reporting a full recovery to zero symptoms, may be subsumed in cases whose preoperative dysfunction is at a level less than the absolute MID thresholds (i.e. less than 20-30%).

There is a wide variability in low back related self-reporting of pain and function, which is known to be a personal experience with multidimensional influences (Rodriguez 2001; Mannion et al. 2005a; Lauridsen et al. 2009). As this thesis investigation shows, even a cohort representing a subset of patients in the small proportion of chronic back-related sufferers that progress to surgical intervention after failure of non-operative interventions, can present with pain and dysfunction at levels (within a day) that are less than MID thresholds. It is clear that these patients require representation, particularly in clinical observational trials assessing the effectiveness of an intervention, such as this study.

It may be argued that an average rating of pain and function over the 4 weeks prior to surgery may have been more appropriate for the present investigation than the daily symptoms used, given the patients were regarded as having a chronic condition (Mannion et al. 2007). It is however the authors experience, based on comments left on each survey, that subjects in the present cohort did refer to longer term recollections of pain and dysfunction when completing their questionnaires. Asking for the daily pattern was intended to steer subjects toward their recent ratings for HRQoL variables.

Limitations

Buttock pain is a common complaint in lumbar degenerative disorders, which presents a problem for defining the location of the symptoms into either the back or leg. In the present study, the decision to classify their region of pain was made by individual patients, and their VAS questions were answered accordingly. Although this did not present an issue for reporting serial pain within an individual, when group back and leg pain were considered, distinction between the two may have been blurred and contributed to the variability seen for the group, particularly at baseline. In particular, this lack of clarity for patients may have affected the results reporting leg pain relative to back pain in terms of response to surgery. Including a body chart as part of the questionnaire may mitigate any doubt as to each patient's pain location when comparing cases within a cohort.

Using the last observed value to impute for missing data at a later point in the study means that for 'failed' cases that progressed to further surgery, a high observation was carried forward, resulting in an overestimation of the true end-of-study measurement. Likewise, had a case been lost to follow-up as a result of changing geographies, but whose last outcome was low because they had responded positively, potential for that value to be an underestimation of the individuals true final outcome existed.

Other confounders on outcome that may not have been recorded if they weren't communicated to the surgeon might have occurred as part of an individual's postoperative course. Manual therapies like physiotherapy, chiropractic, or soft tissue massage, may have been undertaken but not reported by the patient. Additionally, interventional therapies including facet joint injections or nerve root sleeve blocks may have been used in the presence of ongoing symptoms. These interventions all have the potential to influence short-term symptoms over a two year postoperative course, and therefore should be factored into outcome assessment. It was hoped that the comments section of the questionnaire would attract these types of revelations, but this was not generally the case. Future investigations should consider including an additional question in the survey that solicited a response about non-surgical treatments between the completions of each time-point survey.

7.5 Conclusions

Back pain showed early (to 3 months) clinically important improvement after DIAM-augmented lumbar surgery, deteriorating to two years postoperatively when minimal clinical improvement had occurred. Leg pain and function showed minimal clinically significant improvement at each time-point out to two years postoperatively. Best improvement for back pain, leg pain and function was achieved by 3 months after surgery with gradual deteriorating toward the two year postoperative time-point. According to sub-group analyses several group-types appeared to respond best, these included cases in the following sub-groups: males, disc predominant disease, foraminal stenosis, single level surgeries, primary L4/5 or L5/S1 segment disease, and cases receiving more than one decompression procedure to accompany their DIAM insertion. Cases with more leg pain preoperatively showed the best improvement in leg pain postoperatively.

CHAPTER 8

Surface curvature after surgery augmented with DIAM interspinous implant

8.1 Introduction

Conflicting evidence exists to link different sagittal postures with low back pain in adult populations. A few studies have associated back pain with altered segmental or regional lumbar lordosis and sacral inclination, while the majority of studies report no relationship. These mixed results are highlighted in Table 8.1, which summarises investigations describing static lumbosacral sagittal curvature in low back pain, as measured using surface curvature assessment devices.

Table 8.1: Summary of studies that employed manual devices to estimate standing lumbar lordosis (LL) and sacral (or pelvic) inclination (SI) in adults with low back pain versus those without.

Study	**Participants**	**Methods**	**SI in LBP**	**LL in LBP**
Mannion et al, 2005	Pre-op DH n=33 ($\bar{x}$57yrs; F9,M24), Controls n=43 ($\bar{x}$57yrs; F17,M26)	Spinal Mouse; tangent	NR	Reduced in Preop DH
Norton et al, 2004	LBP n=128 (72% >7weeks), $\bar{x}$42yrs, Controls n=60 $\bar{x}$39yrs; (F55%,M45%)	Metrecom; tangent; Pt reported pain & clinical exam categorisation	NR	NS
Nourbakhsh et al, 2002	Mixed n=600	Flexible ruler; tangent	NR	NS
Ng et al, 2002	LBP >12m n=15; controls matched n=15	Inclinometer; tangent	NR	NS
Nourbakhsh et al, 2001	Mixed n=840	Flexible ruler; tangent	NR	NS
Youdas et al, 2000	Mixed n=60 CLBP (55yrs; F30, M30), Controls n=F45, M45	Flexible curve; tangent	NS	NS
Adams et al, 1999	Health care volunteers n=403 (F371, M32); 18-40yrs ($\bar{x}$27)	Isotrak (L1-sacrum); tangent; 5 psychometric questionnaires	Reduced in ‘serious’ LBP	Reduced in ‘serious’ & ‘any’ LBP
Christie et al, 1995	LBP (chronic) n=39; controls n=20	Lateral photographs; standing; tangent	NR	Increased
Waddell et al, 1992	20-55yrs; LBP >3m n=120; controls n=77	Inclinometer; standing; tangent	NR	NS
Bergenudd et al, 1989	Mixed n=575 (F44%); 29% point prevalence for LBP	Spinal pantograph; standing	NR	NS
Dieck et al, 1985	Female college graduates n=871	Lateral photographs; standing; pain survey 25yrs later	NS	NS
Day et al, 1984	Males: LBP n=15; Controls n=32	Standing	NS	NS

Participants=demographics; Methods=Device, mathematical method, determination of LBP; SI=Sacral (or pelvic) inclination; LL=lumbar lordosis; LBP=Low back pain; Pre-op DH=Preoperative disc herniation patients; NR=Not reported; NS=Not significant ($p \geq 0.05$)

A recent meta-analysis reviewing 54 pre-2008 original skeletal and surface-based investigations, did not support an association between spinal health and sagittal spinal curvature (Christensen and Hartvigsen 2008). Postural changes in those in pain are anticipated over time as symptoms and the condition alter (Waddell et al. 1992; Norton et al. 2004); although no investigations using skin surface measurement instruments were identified to support this contention for static standing. Despite the poor consensus on whether a relationship exists, deviations from an 'ideal' posture have been linked to subgroups of back pain (Christie et al. 1995; Adams et al. 1999; O'Sullivan 2005; Smith et al. 2008). Results described earlier in Chapter 5 indicated a repeatable posture in healthy asymptomatic adults over two years, despite the presence of physiological balance strategies like postural sway [Appendix VIII.1-3]. Contrary to hypothesised expectations, the results described in Chapter 6 detected a small flattening (3º) at six weeks postoperatively of the surface lumbar lordosis in a pilot subset of ten cases receiving DIAM-augmented surgery when compared with ten healthy volunteers (Crawford et al. 2009b). Subtle postoperative flattening in surface-derived LL (by 3.7º), was shown by Mannion et al (2005) using the Spinal Mouse system, for 33 patients after lumbar decompression surgery for disc herniation. Whether minor postoperative flattening of LL remained true for more cases in the prospective DIAM cohort over an extended time frame, was of critical interest in this thesis investigation.

An additional consideration in the analysis of this section was the anecdotal observation from neurosurgeons using the DIAM that their patients stood up straighter postoperatively. The surgeons believed this to result from being more comfortable in positions of extension subsequent to surgery (Malone 2007b; Popovic 2007; Taylor 2010). The original hypothesis that no demonstrable regional change to surface lumbar curvature, as determined via rasterstereography, would occur after lumbar surgery augmented with DIAM interspinous implant, was therefore tested.

8.2 Methods

The rasterstereography methods used for deriving surface curvature over two years in a cohort of 39 cases were outlined in Chapter 3.6.3. Serial assessments were undertaken at six time-points: preoperative baseline, 6 weeks, six, 12, 18 and 24 months postoperatively. Patients were imaged using a standardised position and image production technique, while standing in the clavicle position (Figure 3.5). Surface curvature variables included: lumbar lordosis (LL); depth of the lumbar apex (LD); pelvic inclination (PI); thoracic kyphosis (TK); thoracolumbar sagittal balance (SB); and the ratio representing TK divided by LL (refer to Figure 3.7). Early and late change to surface curvature was measured in 39 cases between the baseline and six weeks, and baseline and 18 or 24-month time-points, respectively, using paired t-tests. Baseline unpaired comparisons to the healthy volunteers already reported in Chapter 5 were made. Serial change over a year postoperatively was analysed with Scheffe's post-hoc test in the 27 cases with data at all four time-points. A probability of $p<0.05$ was used to represent a significant difference.

8.3 Results

General: Of the sample of 39 cases comparing change at 6 weeks, 17 were women. Of the sample of 24 cases used for serial comparisons, 11 were women. Mean (SD) age of the 39 patients preoperatively was 54.2 years (10.9) [females 57.5 yrs (6.7); males 51.6 years (12.9)]. Of the women there were 2 cases younger than 50 years (mean 45.5; SD 4.9) and 15 cases 50 years or older (mean 59.1; SD 10.9). There were 9 men aged younger than 50 years (mean 38.7; SD 11.6), while 13 were 50 years or older (mean 60.6; SD 11.1). Despite there being more older women than men, there was no statistical difference in age by gender ($p=0.09$; Figure 8.3).

Baseline values*:* Baseline results for each surface variable assessed and according to gender are summarised in Table 8.2.

Table 8.2: Mean (SD) [95% CI] values for surface curvature as assessed with rasterstereography over the early (n=39) and longer (n=24) postoperative time-points.

		n=39 (F17, M22)			**n=24 (F11, M13)**	
		B	6w	6w-B	18/24m	24m-B
LL	F	50.1 (8.0)	45.3 (6.1)	-4.8 (6.1)	53.4 (6.0)	0.4 (7.1)
	M	35.1 (9.4)^{3}	35.8 (6.5)	0.0 (6.2)^{1}	35.6 (7.7)	-1.5 (6.2)
	All	42.0 (11.3)	39.9 (7.9)	-2.1 (6.5) [0.04,-4.2]	43.8 (11.3)	-0.6 (6.5) [3.8,-7.5]
LD	F	55.5 (12.5)	49.6 (10.6)	-5.9 (7.6)	54.4 (13.1)	1.3 (3.0)
	M	53.1 (12.1)	49.1 (10.3)	-4.0 (5.2)	55.1 (11.8)	-1.1 (4.6)
	All	54.2 (12.2)	49.3 (10.3)	-4.8 (6.3) [2.8,-6.9]^{3}	54.8 (13.0)	0.0 (4.0) [0.9,-5.8]
PI	F	17.9 (6.9)	17.4 (5.3)	-0.5 (4.1)	19.8 (6.3)	0.7 (3.2)
	M	11.4 (6.4)^{2}	10.7 (5.7)	-0.7 (2.9)	10.9 (5.4)	0.3 (2.8)
	All	14.2 (7.3)	13.6 (6.4)	-0.6 (3.4) [0.5,-1.7]	15.0 (7.3)	-0.5 (2.9) [2.2,-2.8]
TK	F	69.4 (11.0)	66.1 (12.0)	-3.3 (5.9)	70.8 (10.2)	5.3 (17.1)
	M	57.3 (8.9)^{3}	56.2 (7.4)	-1.1 (3.9)	56.9 (10.1)	-1.1 (3.8)
	All	62.6 (11.5)	60.5 (10.7)	-2.1 (4.9) [0.4,-3.6]^{1}	63.2 (12.2)	1.9(12.1)[3.7,-16.5]
SB	F	32.7 (23.3)	37.1 (27.8)	4.4 (21.1)	32.8 (13.1)	2.3 (17.5)
	M	21.6 (28.9)	21.3 (28.5)	-0.3 (19.8)	20.1 (19.9)	1.2 (22.2)
	All	26.5 (26.8)	28.2 (29.0)	1.7 (20.2) [8.3,-4.8]	25.9 (18.0)	1.7(19.8)[16.1,-18.3]
T:L	F	1.4 (0.3)	1.5 (0.3)	0.1 (0.2)	1.3 (0.3)	0.03 (0.2)
	M	1.7 (0.5)^{1}	1.6 (0.3)	-0.1 (0.4)	1.7 (0.4)	0.07 (0.3)
	All	1.6 (0.5)	1.6 (0.3)	-0.02 (0.3) [0.1,-0.1]	1.5 (0.4)	0.05 (0.3) [0.3,-0.2]

B=baseline; 6w=six weeks postoperatively; 6w-B=change between baseline and six weeks; 18/24m=latest of 18m or 24 month postoperative data; 24m-B=change at 2 years compared to baseline; F=females; M=males; All=all cases as indicated by the relevant n; LL=lumbar lordosis (˚); LD=lumbar depth (mm); PI=pelvic inclination (˚); TK=thoracic kyphosis (˚); SB=thoracolumbar sagittal balance (mm); T:L=ratio between TK/LL; $^{1}p<0.05$; $^{2}p<0.01$; $^{3}p<0.001$

Mean (SD) baseline values for the group (n=39) were: LL: 42.0˚ (SD 11.3); LD: 54.2mm (12.2); PI: 14.2˚ (SD 7.3); TK: 62.6˚ (SD 11.5); SB 26.5mm (SD 26.8); and TK/LL: 1.6 (SD 0.5) (Table 8.2). Differences in surface curvature variables between genders were apparent at baseline (F n=17; M n=22) with women having significantly greater LL (by 15˚; p<0.001), PI (by 6.5˚; p<0.01) and TK (by 12˚; p<0.001) than men, and a lower TK/LL ratio (by 0.3; p<0.05) (Table 8.2). No differences according to gender for LD or SB at baseline were noted.

Comparisons of the mean values obtained at baseline for the 39 surgical cases studied, with the mean results for the 11 healthy volunteers reported in Chapter 5, are presented in Table 8.3. No differences at baseline between healthy and surgical cases were noted for LL, TK or SB; however PI was significantly less in the surgical cohort (by 7.2˚; p<0.01). No differences in baseline curvature were detected according to age, or anatomical and diagnostic classifications.

Table 8.3: Mean (SD) values for surface curvature as assessed with rasterstereography in 11 healthy volunteers and 39 DIAM-augmented lumbar surgery cases at baseline indicating the mean difference between the two groups [p<0.05].

	Healthy	**Surgical**	**Mean difference [p-value; 95% CI]**
LL	45.6 (10.8)	42.0 (11.3)	-3.6 [p=0.35; 4.1,-11.2]
PI	21.4 (6.2)	14.2 (7.3)	-7.2 [p=0.005; 2.3,-12.1]
TK	58.6 (14.8)	62.6 (11.5)	4.0 [p=0.35; 12.4,-4.5]
SB	26.6 (24.7)	26.5 (26.8)	0.1 [p=0.99; 18.0,-18.2]

Early and long-term paired comparisons*:* Change to surface curvature in the early (baseline compared with six weeks; n=39) and long term (baseline compared with the latest of 18 or 24 months; n=24) postoperative periods are presented in Table 8.2 according to group and gender. LD and TK were shown to reduce at six weeks postoperatively [LD: by 4.8mm (6.3), p<0.001; TK: by 2.1˚ (4.9), p<0.05] compared to baseline. Women and men behaved differently in terms of early change in LL (6w-B; p<0.05), with the female cases reducing by 4.8˚ (6.1) while male cases stayed the same [0.0˚ (6.2)]. No variable had changed significantly at two years compared to baseline. Additional subset analyses according to gender are provided later in relation to the group used for serial comparisons.

Figure 8.1 illustrates the individual case results for LL, PI, TK and SB, with all available time–point data included for each of the 39 subjects assessed at baseline (n=39). Subject numbers were fewer at 12 months postoperatively (n=27) compared to 6 weeks (n=39), with fewer patients again being assessed at 18 months and two years postoperatively (n=24) (refer to Figure 3.2). This declining dataset related to patients being lost to follow-up as a consequence of needing repeat surgery or being unable or unwilling for repeat assessment.

Serial comparisons: Figure 8.2 presents the serial results for age, LL, LD, PI, TK and GSB over the year for 27 DIAM-augmented surgery cases for which all four intra-year time-points were available. No significant differences for LL, PI, TK and GSB were noted over the full period of observation when treated as a group. LD reduced by 5.2mm (p<0.001) at 6 weeks, and then increased to 6 months (by 4.2mm; p<0.001), increasing again to 12 months (compared to the 6 weeks reduced depth; by 4.9mm; p<0.001) such that no difference was apparent between one year and preoperative baseline.

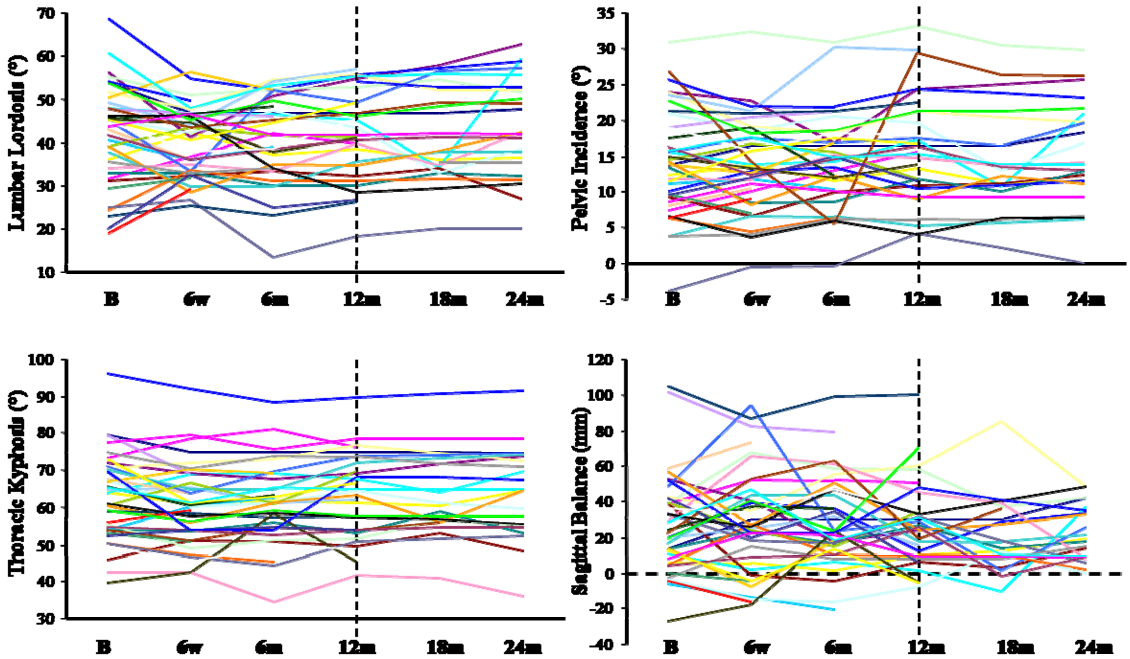


Figure 8.1: Line charts representing rasterstereographic results for LL, PI, TK and SB, assessed over two years for a cohort of 39 patients who received lumbar surgery augmented with DIAM.

Figure 8.3 presents results for LL, LD, PI, TK, GSB and T:L according to gender (F13, M14) revealing significant differences in preoperative LL and TK (p<0.01), and significant flattening of LL and LD in females at six weeks, which then significantly increased by 12 months to approximate preoperative angulation and depth, respectively. Male cases showed changes to surface LD during the postoperative year, with a reduced depth at 6 weeks (5.0mm; p<0.001), followed by progressive increases at 6 months (4.9mm; p<0.001), and 12 months (5.6mm; p<0.001) compared to the 6 weeks LD values.

Of the 27 subjects in the serial comparison group, all cases received DIAM implants at or caudal to L3/4. Sixteen patients were implanted with a single DIAM, eight with two implants, and three with three devices.

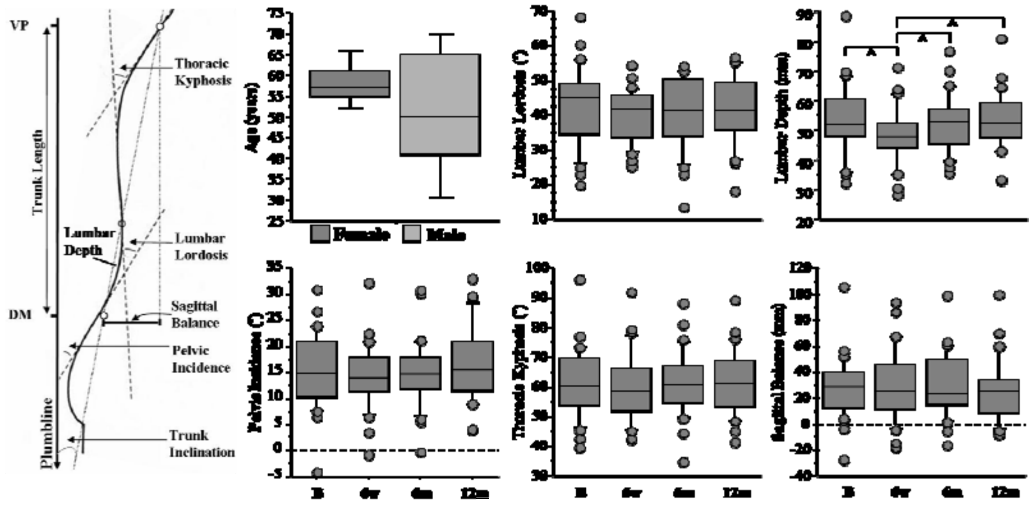


Figure 8.2: Box-plots (with outliers) representing: age according to gender (NS); and the serial change in lumbar lordosis (LL), lumbar depth (LD), pelvic inclination (PI), thoracic kyphosis (TK) and sagittal balance (GSB) for 27 cases that received lumbar surgery augmented with the DIAM interspinous implant. Preoperative baseline, 6 week, 6 and 12 months postoperative time-points are presented. Horizontal lines from the top represent 10th, 25th, 50th, 75th and 90th percentiles, respectively. No statistically significant differences (p<0.05) were seen for any variable over the full year; however there were significant changes in LD between certain time-points within the 12 month observational period (p<0.001).

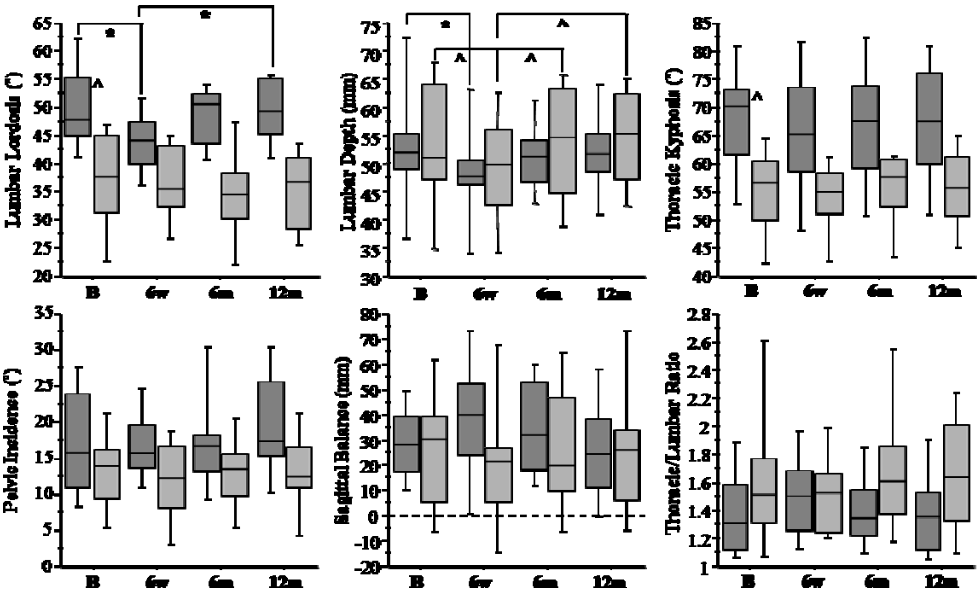


Figure 8.3: Box-plots representing the serial change in lumbar lordosis (LL), lumbar depth (LD), pelvic inclination (PI), thoracic kyphosis (TK), sagittal balance (GSB) and TK/LL ratio according to gender for 27 cases [F13 (dark), M14 (light)] that received lumbar surgery augmented with the DIAM interspinous implant. Preoperative baseline, 6 week, 6 and 12 months postoperative time-points are presented. Horizontal lines from the top represent 10th, 25th, 50th, 75th and 90th percentiles, respectively. Females had significantly greater LL and TK at baseline compared to the male cases (^p<0.01), and had reduced LL and LD at 6 weeks, which increased to 12 months postoperatively (*p<0.05). Males had reduced LD at 6 weeks, which increased to 12 months postoperatively (^p<0.01).

The level categorised as the segment comprising the most significant pathological involvement toward which the surgery was primarily directed was L4/5 (n=14), L5/S1 (n=9) and L3/4 (n=4). Eleven cases were categorised with primary disc involvement, 11 with predominant facet pathology, and five with mixed segment disease. Diagnostic categorisation included 15 with lumbar spinal stenosis (LSS; foraminal=13, central canal=2), seven with degenerative spondylolisthesis (DS) and five with facet joint pain syndrome (FJPS). Subset analyses according to age (<50yrs<); anatomical; and diagnostic classifications; and number of DIAMs implanted, for LL, TK and LD are presented in Figures 8.4-6, respectively.

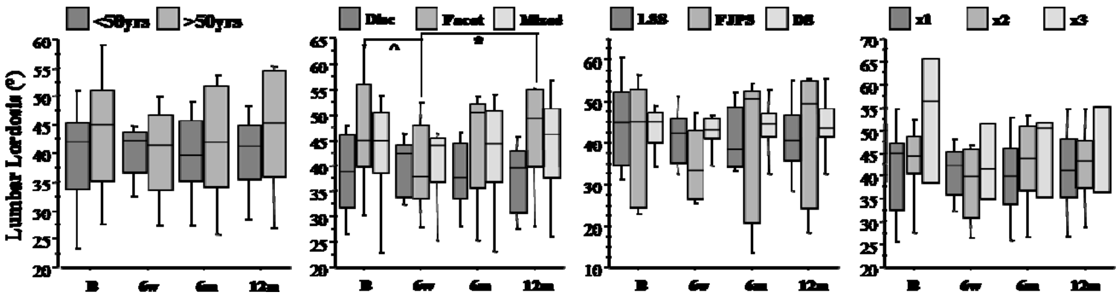


Figure 8.4: Box-plots representing the serial change in lumbar lordosis (˚) for 27 cases according to age (<50yrs n=8; >50yrs n=19), anatomical classification (disc n=11; facet n=11; mixed n=5), diagnoses [LSS lumbar spinal stenosis (n=15); FJPS facet joint pain syndrome (n=50); DS degenerative spondylolisthesis (n=7)], and number of DIAMs implanted (1 n=16; 2 n=8; 3 n=3). Horizontal lines from the top represent 10th, 25th, 50th, 75th and 90th percentiles, respectively. Cases with facet pathology showed initial flattening at 6 weeks postoperatively (^p<0.01), which then returned to preoperative values at 12 months (*p<0.05).

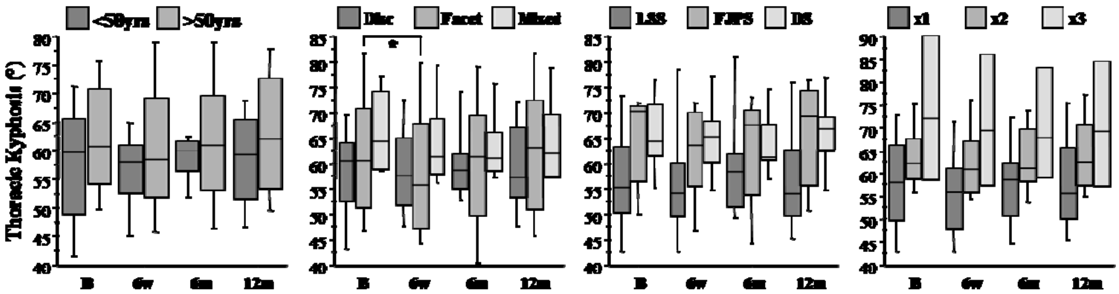


Figure 8.5: Box-plots representing the serial change in thoracic kyphosis (˚) according to age (<50yrs n=8; >50yrs n=19), anatomical classification (disc n=11; facet n=11; mixed n=5), diagnoses [LSS lumbar spinal stenosis (n=15); FJPS facet joint pain syndrome (n=5); DS degenerative spondylolisthesis (n=7)], and number of DIAMs implanted (1 n=16; 2 n=8; 3 n=3). Horizontal lines from the top represent 10th, 25th, 50th, 75th and 90th percentiles, respectively. Cases with facet pathology showed initial flattening at 6 weeks postoperatively (*p<0.05).

For LL and TK, no significant change within the year occurred according to age, diagnostic classification or the number of DIAMs implanted. Cases with predominant facet dysfunction (n=11) had reduced LL (by 7.4º; ^p<0.01) and TK (by 3.3º; *p<0.05) at 6 weeks compared to baseline, with LL significantly increased at 12 months compared to their 6 weeks time-point (by 5.6º; *p<0.05).

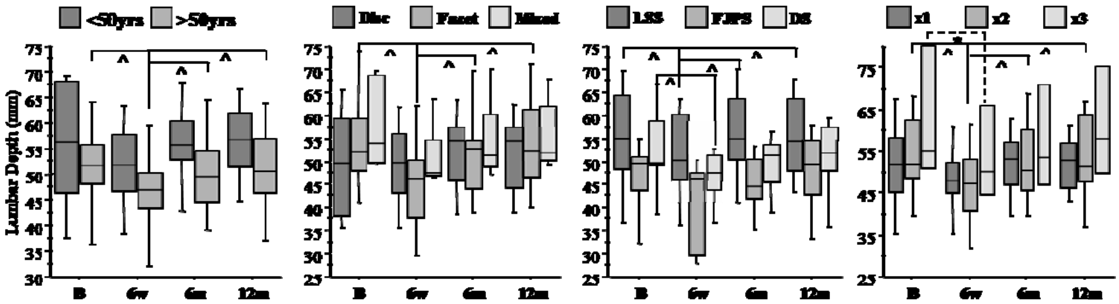


Figure 8.6: Box-plots representing the serial change in lumbar depth (mm) according to age (<50yrs n=8; >50yrs n=19), anatomical classification (disc n=11; facet n=11; mixed n=5), diagnoses [LSS lumbar spinal stenosis (n=15); FJPS facet joint pain syndrome (n=5); DS degenerative spondylolisthesis (n=7)], and number of DIAMs implanted (1 n=16; 2 n=8; 3 n=3). Horizontal lines from the top represent 10th, 25th, 50th, 75th and 90th percentiles, respectively. Cases older than 50 years, with facet pathology, spinal stenosis, or implanted with 2 DIAMs showed initial flattening at 6 weeks postoperatively (*$p<0.05$; ^$p<0.01$), then increasing again by 6 and 12 months compared to the 6 week time-point. No significant difference was noted at 12 months compared to baseline.

Various subsets of the 27 cases serially assessed revealed change over the course of the year to the depth of the lumbar curvature at its apex (Figure 8.6). Those aged over 50 years (n=19), cases with predominant facet pathology (n=11) or diagnosed with lumbar spinal stenosis (n=15), and particularly cases implanted with two DIAMs (n=8), had a reduced LD at 6 weeks compared to baseline ($p<0.001$), which increased significantly at 6 ($p<0.001$) and 12 months ($p<0.001$) when compared to the flattened 6 week postoperative values.

Relationships between variables at preoperative baseline: Correlations between surface curvature variables obtained at preoperative baseline for the 27 cases for which all time-point data were available are presented in Table 8.4. A strong relationship was shown between LL and T:L ($r=-0.78$; $r^2=0.61$; $p<0.0001$). A moderate relationship was noted between LD and TK ($r=0.62$; $r^2=0.38$; $p<0.001$). Modest relationships were detected between: LL and TK ($r=0.52$; $r^2=0.27$; $p<0.01$), SB and T:L ratio ($r=0.48$; $r^2=0.23$; $p<0.05$), LL and PI ($r=0.46$; $r^2=0.21$; $p<0.05$), LL and LD ($r=0.43$; $r^2=0.18$; $p<0.05$) and PI and T:L ($r=-0.42$; $r^2=0.18$; $p<0.05$). No other significant relationships existed.

Relationships between variables according to change between time-points: Correlations for change between six weeks and baseline and 12 months and baseline for the 27 cases for which all time-point data were available are presented in Table 8.5. A strong relationship was shown between change in LL and change in TK/LL ratio (T:L) at the 6 weeks and 1 year comparisons to baseline ($r=-0.87$; $r^2=0.76$; $p<0.0001$). Moderate correlations were seen between LD and TK at both time-point comparisons (6w-B $r=0.63$, $r^2=0.40$, $p<0.001$; 12m-B $r=0.68$, $r^2=0.46$, $p<0.001$). Modest relationships were detected between: LL change and TK change at 6 weeks ($r=0.52$; $r^2=0.27$; $p<0.01$) and LL change and PI change at 12 months ($r=0.41$; $r^2=0.17$; $p<0.05$).

No other significant relationships existed.

Table 8.4: Matrix representing correlations [r-values] between surface curvature variables at baseline as assessed via rasterstereography in 27 cases that received decompressive lumbar surgery augmented with DIAM interspinous implant. Statistically significant relationships between lumbar lordosis (LL), lumbar depth (LD), pelvic incidence (PI), thoracic kyphosis (TK), sagittal balance (SB) and the ratio defined by TK divided by LL (T:L), are indicated.

	Baseline Associations				
	LD	PI	TK	SB	T:L
LL	0.43[1]	0.46[1]	0.52[2]	-0.29	-0.78[3]
LD		0.00	0.62[3]	-0.11	-0.09
PI			-0.01	0.11	-0.42[1]
TK				0.05	0.07
SB					0.48[1]

Statistical significance: [1]$p<0.05$; [2]$p<0.01$; [3]$p<0.001$

Table 8.5: Matrix representing correlations [r-values] between change in surface curvature variables between six weeks (top right corner), and 12 months (bottom left corner) and baseline, as assessed via rasterstereography in 27 cases that received decompressive lumbar surgery augmented with DIAM interspinous implant. Statistically significant relationships between lumbar lordosis (LL), lumbar depth (LD), pelvic incidence (PI), thoracic kyphosis (TK), sagittal balance (SB) and the T:L ratio (TK divided by LL), have been indicated in bold.

		Six weeks-Baseline Associations				
12m-B	LL	LD	PI	TK	SB	T:L
LL		0.45[1]	0.24	0.52[2]	-0.29	-0.87[3]
LD	0.24		-0.40[1]	0.63[3]	-0.20	-0.34
PI	0.41[1]	-0.12		-0.07	-0.01	-0.30
TK	0.29	0.68[3]	-0.21		-0.21	-0.18
SB	-0.17	-0.16	-0.06	-0.04		0.25
T:L	-0.87[3]	-0.04	-0.31	-0.01	0.12	

Statistical significance: [1]$p<0.05$; [2]$p<0.01$; [3]$p<0.001$

8.4 Discussion

The results of this study of spinal alignment and curvature employing rasterstereography have shown that for the 27 cases with all three time-point data, lumbar surgery augmented with the DIAM interspinous implant resulted in significant reduction to the depth of the lumbar apex in the early postoperative period but had no effect on LL, LD, PI, TK, or SB, at one year after surgery compared to baseline. To the knowledge of the author, only one other study has investigated spinal posture using a surface-based system (spinal mouse) in adult patients after lumbar surgery (Mannion et al. 2005b). Pre and early postoperative (2 months) lumbar lordosis in standing were described by Mannion et al in patients over 45 years or age that received decompression surgery for disc herniation. No other variables measured in upright standing were reported in their series, where range of lumbar sagittal motion was the main study focus in relation to patient-reported pain and function. The present study, reporting a range of surface-derived variables for spinal curvature, therefore represents an original contribution to the literature for which no comparative data exists.

The results described earlier in Chapter 6 detected a small flattening (3º) at six weeks postoperatively of the surface lumbar lordosis (LL) in a subset of ten cases receiving DIAM-augmented surgery, when compared with ten healthy volunteers (Crawford et al. 2009b). This result agreed with the findings of Mannion et al (2005) who also reported LL flattening (3.7º), at 2 months after decompression surgery in their 33 cases with disc herniation. However, when paired comparisons were applied to the 39 cases in the prospective cohort of the present series, for which baseline and six weeks data were available, the small (2º) flattening detected in LL at 6 weeks was not significant. A non-significant mean flattening of 0.6º was shown in the 24 cases for which 2 year data were available, with the male cases tending to flatten (-1.5º; NS) and the female cases slightly increasing their LL (0.4º; NS). It might therefore be argued that any early flattening after decompression lumbar surgery relates more to postoperative recovery from the decompression component of the surgery than implantation with the DIAM. Mannion et al did not extend their follow-up beyond 2 months, so it is unknown whether their noted change was maintained.

The present surface LL findings must be contextualised in the light of the rasterstereographic system reliability, and the variability of data reported previously for healthy volunteers and the surgical cohort studied in this thesis investigation (Chapters 5 and 6). Drerup (1982) reported system accuracy of 2.8˚ for measuring both TK and LL in vivo, and less than 1˚ for inclination (trunk and PI). Additionally, repeat measures of the thermoplastic back phantom (presented in Chapter 5) showed coefficients of variation (CV) <1% (and SD <0.2˚) for TK and LL, <2% for PI (SD <0.3˚), and 4% CV for SB (SD 0.4mm). Repeat intra-session measures of 10 healthy volunteers and 10 surgical cases reported in Table 6.1, revealed comparable SD ranges for LL between 0.2 to 2.6˚ and 0.2 to 1.8˚, respectively. Similarly, ranges of SD that were reported per 5-trial session for each variable for the 11 healthy volunteers presented in Chapter 5 were: LL=0.2 to 3.6˚ (Table 5.2); TK=0.4 to 4.9˚ (Table 5.3); PI=0.2 to 3.8˚ (Table 5.4); and SB=1.9 to 13.2mm (Table 5.5). Individual change in excess of the upper limit of each of these ranges might therefore be considered beyond what is expected in normal variation. The small change observed in the 39 surgical cases described in this series is probably beyond the sensitivity of the rasterstereographic method employed.

When the group was split according to gender (refer to Table 8.2), female subjects (n=17) had an appreciable flattening of LL at six weeks postoperatively compared to baseline (by 4.8º), while male subjects (n=22) showed no change. The different early change seen between genders is not surprising given the female cases had a greater mean LL preoperatively than the men (by 15º; p<0.001) and therefore had arguably more potential for reduction. The serial comparisons for the 27 cases where all four intra-year time-point data were available, also revealed no significant change in LL when treated as a group, yet when split according to gender, showed women with a reduced LL at six weeks, while men did not change. These findings suggest that LL, as assessed from the skin surface using rasterstereography, is affected differently in women than men after lumbar surgery augmented with DIAM. This may relate to women having greater LL than men (Youdas et al. 1996; Norton et al. 2004; Youdas et al. 2006) before surgery and therefore a higher angulation to reduce from.

In conflict with the notion that those with higher angulation preoperatively (e.g. women) might be more likely to have a postoperative reduction, thoracic kyphosis was also significantly higher in females preoperatively, yet neither gender showed significant change postoperatively when serial comparisons were made (Figure 8.3 and Table 8.2). Interestingly, the baseline-six weeks TK comparisons for 39 cases showed a mild group flattening (by 2º; $p<0.05$) at six weeks after surgery. This result may lend weak support to the anecdotal observations from surgeons that patients straighten their spines after surgery augmented with DIAM (Malone 2007b; Popovic 2007; Taylor 2010), although the clinical significance of this appears doubtful given the minor angular change detected.

The baseline differences noted in this study between genders appear in agreement with the studies reported in Table 2.x that indicate women have more LL and TK on average than males. The mean (SD) LL [42º (11)] and TK [62º (11)] reported in the 39 surgical cases was comparable to that reported for the 11 healthy cases of a wide age range [LL 45 º (10); TK 58º (14)], while the mean pelvic inclination for the surgery cases [14º (7)] was significantly less ($p<0.01$) than in the healthy cases [21º (6)] (Table 7.2.3). These results therefore agree in part with the study of Adams et al (1999) who employed the Isotrak to assess surface spinal lumbar curvature in health care workers (outlined in Table 8.1). They found that reduced sacral angle (in relation to the vertical) was associated with a reported episode of 'serious' back pain (Adams et al. 1999). They also showed that those with reduced lordosis were more likely to report back pain than those without, which conflicted with another study that reported an increased LL in low back pain (Christie et al. 1995), or, like the results of the present series, studies that report no association (Day et al. 1984; Dieck et al. 1985; Bergenudd et al. 1989; Waddell et al. 1992; Youdas et al. 2000; Ng et al. 2001; Nourbakhsh et al. 2001; Nourbakhsh and Arab 2002; Norton et al. 2004). The weight of evidence based on measurements using surface curvature instruments indicates that no relationship exists between the angle of lumbar lordosis and the presence of low back pain. The limited evidence reporting on surface sacral inclination makes a relationship with back pain difficult to conclude.

The mean SB reported preoperatively [26.5mm (26.8)] in the 39 baseline cases is at the outer limit of what is regarded as acceptably positive for normal (based on skeletal measurements) (Jackson and McManus 1994; Jackson and Hales 2000). In comparison though, the 11 healthy subjects reported in Chapter 5 who were assessed using the same device and with the same method as the present surgical group (but for arm position), had virtually the same average [26.6mm (24.5); NS] forward lean in standing. It might be argued that the influence of arm position on the surgical subjects (explored in Appendix VII.2) resulted in their having slightly less LL or a more neutral SB than would have been true if they had been measured with their arms by the side (as was so for the healthy cases). Despite this reservation, the mean SB reported for the surgical cases appears comparable to the healthy volunteers and therefore suggests no influence of back pain on SB, where this is measured via rasterstereography from the skin surface, as described in this study. The influence of pain and function on spinal curvature is elaborated further in Chapter 10.

No difference in LD according to gender was demonstrated preoperatively in either the initial 39 cases or in the 27 cases where all serial time-point data within a year were available (Table 8.2 and Figures 8.2&3). Serial comparisons showed that both genders had an early reduction in LD at 6 weeks after DIAM-augmented surgery (females $p<0.05$; males $p<0.01$), yet no change was noted at 12 months compared to preoperative values for either gender. However, male cases increased significantly at 6 and 12 months when referenced to their reduced 6 week values (Figure 8.3). LD, derived via video rasterstereography in this study, refers to the depth of the apex (or peak) of the lumbar shape, which reports intraregional, segmental characteristics (Drerup and Hierholzer 1994). LL on the other hand is defined by the intersection of tangents through the thoracolumbar and lumbosacral inflexion points, therefore representing angulation between end-points of the spinal curvature only. LD was the rasterstereography-derived surface curvature variable that was most influenced by the subset analyses of the 27 cases assessed over one year (Figures 8.3&6). Being aged over 50 years, having predominant facet pathology, a diagnosis of lumbar spinal stenosis, or having received two DIAMs in surgery, determined early reduction in LD that did not persist out to one year. It might be argued that LD reflects a superior variable in describing intraregional shape, than does LL. Consequently, the results of this study indicate a reduced lumbar apex in the first 6 weeks after DIAM-augmented surgery, which returns to preoperative values by one year. Based on this, the author suggests that the depth of the lumbar curvature be included as a variable in reporting surface spinal shape characteristics in adults after lumbar surgery where spinal alignment is purportedly affected by the procedure.

The mean reduction in LD seen for the 39 cases at 6 weeks after surgery was approximately 5mm. The clinical significance of this small difference is therefore questionable and may be related to physiological factors including aspects of tissue healing like effusion, scarring, muscle spasm, or even weight gain as a consequence of being less active in the early postoperative period. Also, if the rasterstereographic system error of 1° for inclination-based variables (like LD) is considered, this 5mm flattening in LD in the surgical cases seems inconsequential. The capacity for rasterstereography to report segmental lumbar shape in this cohort of surgical cases was investigated in the study reported in Appendix VI.2. This exploratory comparison of the curvature profiles of a thermoplastic back phantom, a healthy volunteer and a surgical case from the DIAM cohort, indicated a reduced depth of the lumbar apex in both in vivo subjects, which appeared local to the operation site in the surgical case. A less dramatic reduction was noted for the healthy volunteer, thereby making definitive conclusions difficult; however the study indicated a potential use for rasterstereography, or other light-topography systems, in reporting serial changes to segmental shape within the lumbar region. Further study would need to be undertaken to confirm this utility.

It seems unlikely that the early minor changes noted in this study for LD, LL or TK are clinically significant, given they are small and not sustained at 6 months after surgery compared to baseline. Additionally, the two variables that have been reported to influence pain and function when assessed from skeletal imaging (pelvic incidence and sagittal balance in relation to the sagittal vertical axis) were unchanged at all time-points compared to baseline (Figures 8.2&3). Associations between surface spinal curvature and self-reported pain and function are explored further in Chapter 10.

The strongest baseline and serial change relationships occurred between LL and the ratio between TK and LL (T:L). Given T:L was dependent on LL in its division, the relationship between the two is not surprising. TK and LD were moderately associated at baseline and according to change over time ($r \sim 0.70$; $p<0.001$). At baseline and according to change by 6 weeks, TK and LL were moderately correlated ($r=0.52$; $p<0.01$). Fair relationships were noted between: LL versus LD, LL versus PI, PI versus T:L and SB versus T:L at baseline, and between LL and LD and LD and PI according to change by 6 weeks, and LL compared with PI, based on change at 12 months.

That LD and LL were moderately related to TK at baseline indicates potential for intra-spinal compensation; as thoracic angulation increases, so does the depth or angulation of the lumbar lordosis, the latter being less convincing. Asymmetric loads on the spine resulting from postural deviations are thought to be compensated by adaptation of the body according to Wolff's and Davis's laws, which state that form follows function (in bone and soft tissues, respectively) (White and Panjabi 1978; Stedman 2006). The present study endeavoured to assess whether compensatory postural mechanisms occurred after lumbar surgery augmented with DIAM, although measurements were limited to the sagittal profile of the thoracolumbar spinal contour.

Strong evidence supporting a cause-and-effect compensation within the thoracic and lumbar curves was not found, however the significant association between the thoracic and lumbar curves lends a degree of support for the contention. The potential for any postural compensation to occur at joints removed from those referenced via rasterstereography exists. Hips, knees and ankles have the capacity for a modified angulation in compensation for perturbations to standing balance, and therefore their influence requires acknowledgment. It was believed that perturbations and influences on quiet standing were minimised using the rasterstereography method employed in the present study, where standing balance was not overtly challenged. The influence of postural sway has been previously discussed in Chapter 5 in relation to surface curvature in healthy volunteers, and is the subject of the studies reported in Appendices VII.1-3. Measurements of spinal shape and alignment that reference to the vertical are susceptible to variability, due to the influences of maintaining balance through the physiological mechanism of postural sway. The sagittal view is reported to provide a more stable measure of spinal angulation than the posterior view when photographic imaging is employed (Dunk et al. 2005).

Dunk et al (2005) recommended that if postural analysis is used to detect changes due to treatment interventions, such changes must be larger than the baseline variability seen in healthy subjects. Based on this, the wide range of normative values reported for sagittal curvature in healthy cases (Table 8.3) might question the sensitivity of rasterstereography in detecting a difference after treatment. The standard deviations for the angles of lumbar lordosis, pelvic incidence and thoracic kyphosis in the group of 11 healthy cases of a wide age range were 10º, 6º, and 14º, respectively. Change to surface curvature for the complete series of surgical cases reported in the present chapter (Table 8.2) were less than half these values at best. This potentially questions the utility of rasterstereography as an instrument to detect postural change in adults undergoing minimally invasive lumbar surgery where influence on regional curvature, if any, might be minimal. However, inspection of surface curvature per individual case as presented in the line charts in Figure 8.1 reveals varying change detected within cases over the two year observation period, and may indicate utility for the instrument in reporting serial thoracolumbar sagittal profiles of individuals.

8.5 Conclusions

Women had significantly more lumbar lordosis and thoracic kyphosis preoperatively than men. Sacral inclination in the lumbar surgery cases was less than for healthy volunteers. No change to surface thoracolumbar curvature occurred after a year subsequent to lumbar surgery augmented with DIAM compared to preoperative values. Early (six weeks) reduction in the depth of the lumbar apex was not maintained at 6 months or a year postoperatively. Different responses in surface curvature (particularly LD) after surgery according to gender, age, anatomical and diagnostic classification, and number of implanted DIAMs were noted. Moderate associations between thoracic kyphosis and lumbar lordosis or depth were found.

CHAPTER 9

Lumbar skeletal sagittal alignment after surgery augmented with DIAM interspinous implant

9.1 Introduction

The potential for segmental kyphosis in the presence of a DIAM ISP implant is acknowledged, particularly at the index segment in cadaveric spines (Phillips et al. 2006; Wilke et al. 2008), yet a limited literature has reported skeletal curvature based on radiographic assessments of patients (Kim et al. 2007; Sobottke et al. 2009). Sobottke et al (2009) considered a sub-set of cases that received DIAM-augmented lumbar surgery as treatment for neurogenic intermittent claudication (NIC) secondary to lumbar spinal stenosis (LSS). They observed short term flattening (5° kyphosis) at the index segmental level, as determined from lateral plain radiography imaged with patients in standing. Whether the patients with varied lumbar degenerative pathologies followed in this thesis investigation were similarly skeletally affected by DIAM-augmented surgery, was of interest. It was hoped that the mechanical effect of the device in vivo might be better understood.

The two primary hypotheses relating to this radiographic part of the investigation were that: a skeletal segmental relative kyphosis would be detected at the primary level of DIAM implantation, and; regional lumbar curvature as measured from radiographic imaging would be unchanged after surgery augmented with DIAM interspinous implant.

A few studies have assessed skeletal curvature and alignment in vivo after surgery employing some of the available ISP devices, with spinal alignment and intervertebral, spinal canal and neural foraminal dimensions reported to be affected (Richards et al. 2005; Siddiqui et al. 2006a; Kim et al. 2007; Sobottke et al. 2009). In their series of patients with LSS, Sobottke et al (2009) showed that foraminal height, width and cross-sectional area, intervertebral end-plate angle, and anterior and posterior disc heights were altered subsequent to surgery augmented with each of three interspinous implants; the DIAM, X-Stop and Wallis.

The present study aimed to evaluate the biomechanical impact of surgery augmented with DIAM on the lumbar spine, at regional, operated and adjacent levels, in vivo. Patients were receiving treatment for a variety of pathologies including LSS, degenerative spondylolisthesis (DS) and facet joint pain syndrome (FJPS). Sagittal alignment including lumbar lordosis, sacral inclination, segmental disc angle, lumbar sagittal balance and radius of curvature were examined for a year postoperatively. This study measured regional sagittal balance (RSB) by employing the L1 axis to S1 distance (LASD) as an index for radiologic evaluation (Kawakami et al. 2002). This method has been reviewed in Chapter 2 and its application for this thesis outlined in Chapter 3. Examination of the purported mechanical action of the DIAM may assist in identifying reasons behind the various individual responses to its implantation.

9.2 Methods

The radiographic evaluation procedure has been previously outlined in Chapter 3.6.4. Serial assessments were undertaken at three time-points: preoperative baseline, 6 weeks and 12 months postoperatively. Patients were imaged using a standardised technique for producing lateral sagittal lumbar images while they stood in the clavicle position (Appendix IV). Computed radiographic variables included: lumbar lordosis (LL); sacral inclination (SI); disc angles [at the primary surgical level (PDA), and the level above (supradjacent; SDA)]; regional sagittal balance (RSB), which was also reported relative to the length of the lumbar region between L1 and S1 (RRSB); and mean radius of curvature (RoC) [for the entire lumbar region (RoC1-6) and that local to the primary implant (RoC2+2)] (refer to Figure 3.7).

9.3 Results

General: The gender ratio (F:M) at preoperative baseline (n=62) was 0.8:1, 1:1 for the three time-point serial comparison for the whole group (n=40), and 0.8:1 for the single-DIAM subset (n=22). Mean (SD) age of the 62 patients preoperatively was 52.0 years (14.0) [females 54.8 yrs (11.5); males 49.9 yrs (15.3)]. Of the women, there were 8 cases younger than 50 years (mean 41.4; SD 6.7) and 19 cases 50 years or older (mean 60.5; SD 7.7). There were 17 men aged younger than 50 years (mean 37.0; SD 9.5), while 18 were 50 years or older (mean 62.1; SD 7.5). There was no statistical difference in age by gender.

All cases received DIAM implants at or caudal to L3/4. Thirty-five patients were implanted with a single DIAM, 22 with two implants, and five with three devices. The level categorised as the segment comprising the most significant pathological involvement toward which the surgery was primarily directed was L4/5 (n=32), L5/S1 (n=25) and L3/4 (n=5). The breakdown of cases according to level of DIAM implantation is schematically presented in Figure 9.1. Case numbers according to DIAM device size at the primary implant level were: 8mm (n=14), 10mm (n=13), 12mm (n=11), and 14mm (n=2). Nineteen cases were categorised with primary disc involvement, 16 with predominant facet pathology, and five with mixed segment disease. Diagnostic categorisation included 27 with lumbar spinal stenosis (LSS; foraminal=22, central canal=5), ten with degenerative spondylolisthesis (DS) and three with facet joint pain syndrome (FJPS).

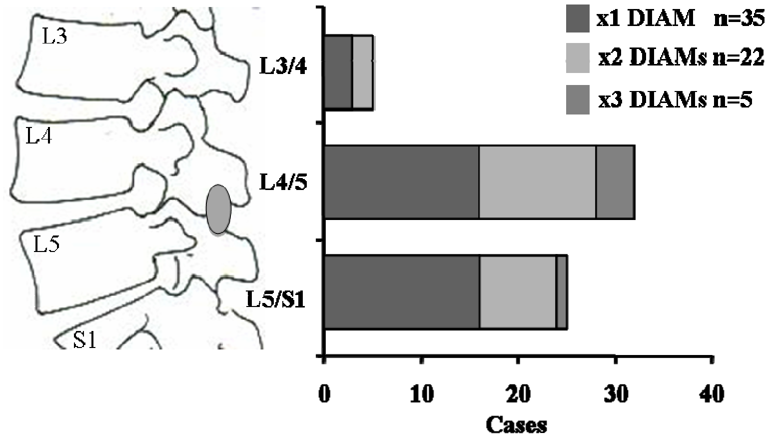


Figure 9.1: Case distribution according to the primary implanted segment in relation to those who received single, double and tri-level DIAMs. The predominance of single-level surgeries directed toward the lowest lumbar intervertebral segments is noted.

Table 9.1: Mean (SD) radiological results at preoperative baseline, 6 weeks and 12 months postoperatively. Paired t-tests were applied to each two time-point comparison using the maximum number of cases available. Significant differences between time-points are noted in bold (p<0.05).

	B-6w (n=59)		**6w-12m (n=40)**		**B-12m (n=43)**		**B-6w-12m (n=40)**		
LL (Cobb L1-S1) (°)	52.7 (11.7)	52.1 (10.5)	**53.3 (10.6)**	**55.3 (9.2)**	52.0 (12.9)	54.2 (9.9)	53.3 (12.3)	53.3 (10.6)	55.3 (9.2)
	p=0.61		**p=0.045**		p=0.09				
Sacral Inclination (°)	-36.0 (6.8)	-35.4 (7.4)	-35.9 (7.0)	-36.7 (6.6)	-35.6 (8.2)	-36.0 (7.1)	-36.4 (7.3)	-35.9 (7.0)	-36.7 (6.6)
	p=0.28		p=0.19		p=0.53				
Primary Disc Angle (°)	**9.8 (5.9)**	**7.6 (4.5)**	7.0 (4.5)	7.7 (4.8)	**9.0 (6.0)**	**7.5 (5.0)**	9.2 (5.7)	7.0 (4.5)	7.7 (4.8)
	p<0.0001		p=0.27		**p=0.03**				
Supradjacent Disc Angle (°)	10.1 (4.8)	9.8 (4.2)	9.8 (4.1)	10.5 (4.4)	9.8 (4.8)	10.5 (4.2)	9.9 (4.9)	9.8 (4.1)	10.5 (4.4)
	p=0.59		p=0.17		p=0.32				
Region Sagittal Balance (RSB)	**3.3 (40.0)**	**9.9 (35.2)**	11.1 (33.7)	9.5 (38.7)	6.2 (38.5)	10.0 (40.1)	5.6 (38.0)	11.1 (33.7)	9.5 (38.7)
	p=0.02		p=0.62		p=0.23				
Relative RSB (RRSB) Ratio	0.02 (0.13)	0.03 (0.12)	0.04 (0.12)	0.03 (0.12)	0.03 (0.13)	0.03 (0.13)	0.03 (0.13)	0.04 (0.12)	0.03 (0.12)
	p=0.06		p=0.79		p=0.14				
RoC (L1-S1)	502 (549)	452 (545)	466 (654)	510 (883)	532 (631)	524 (853)	517 (650)	467 (654)	511 (882)
	p=0.33		p=0.29		p=0.93				
RoC (2+2)	375 (236)	336 (227)	357 (260)	367 (256)	355 (268)	388 (256)	341 (272)	357 (260)	367 (244)
	p=0.75		p=0.78		p=0.46				

B=preoperative baseline; 6w, 12m=6 weeks, 12 months post-op; n=number of a cases used for comparison based on available data for each of the listed time-points; LL=lumbar lordosis; RoC=radius of curvature; L1-S1=inclusive of the superior endplates of the first lumbar and sacral vertebrae; RoC (2+2)=radius of curvature including the vertebrae two levels above and below the index segment.

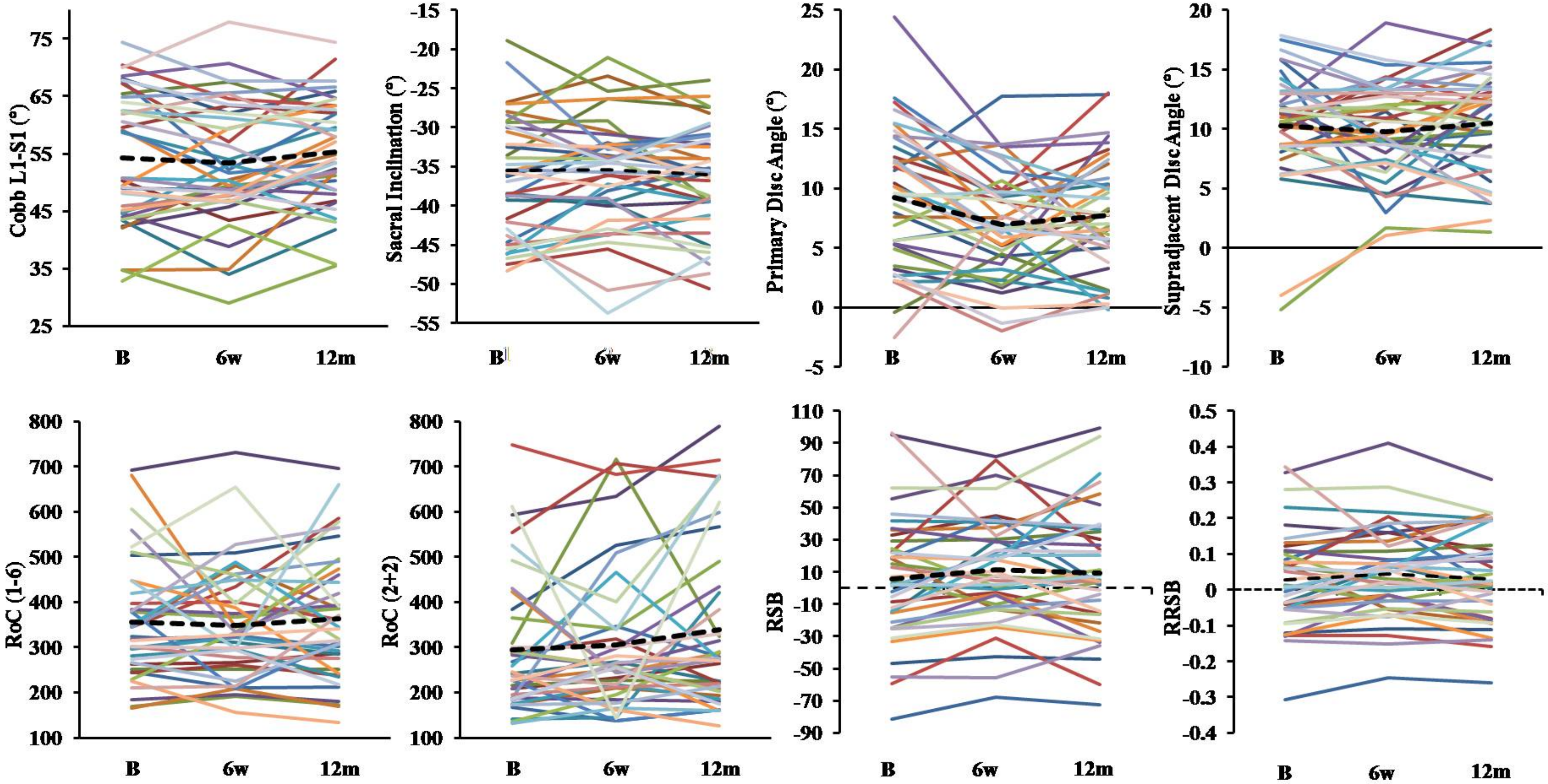


Figure 9.2:Line charts representing radiographic results for all variables assessed over a year for a cohort of 40 patients who received lumbar surgery augmented with DIAM. Definitions for each variable are given in Chapter 3.3. Thick dashed black lines indicate group means for each variable. Coloured lines indicate the data for each individual, which may not correspond across separate charts.

Mean group results for each of the skeletal variables assessed in this study are presented in Table 9.1. Figure 9.2 illustrates the individual case results for each variable, detail of which will be described separately below.

Lumbar lordosis (Cobb L1-S1): Mean LL for the group was 51.8˚ (SD 12.2). The mean female preoperative lumbar lordosis was 54.1˚ (SD 12.6) while the men averaged 50.0˚ (SD 11.7) (NS). No difference in baseline LL for cases younger (52.4; SD 13.8) or older than 50 years (51.5; SD 11.1) was noted (NS). No significant change to LL occurred when compared to preoperative baseline at either post-operative time-point (Table 9.1). There was a mean increase in LL of 2° ($p=0.045$) between the 6 week and 12 month postoperative points according to paired comparison (t-test; n=59), however no significant difference was noted when all three time-points were analysed in the group of 40 cases (Figure 9.3). When the group data was split according to gender, age and primary implant level, a mean increase in LL of 3.6˚ ($p<0.05$) was seen between the 6 week and one year time-points in those older than 50 years, while individuals who received their primary implant at L3/4 showed an increased LL (9.1˚; $p<0.05$) between baseline and 6 weeks and an overall reduction in LL between 6 weeks and one year (5.6˚; $p<0.05$). Results for LL are presented in Figure 9.3.

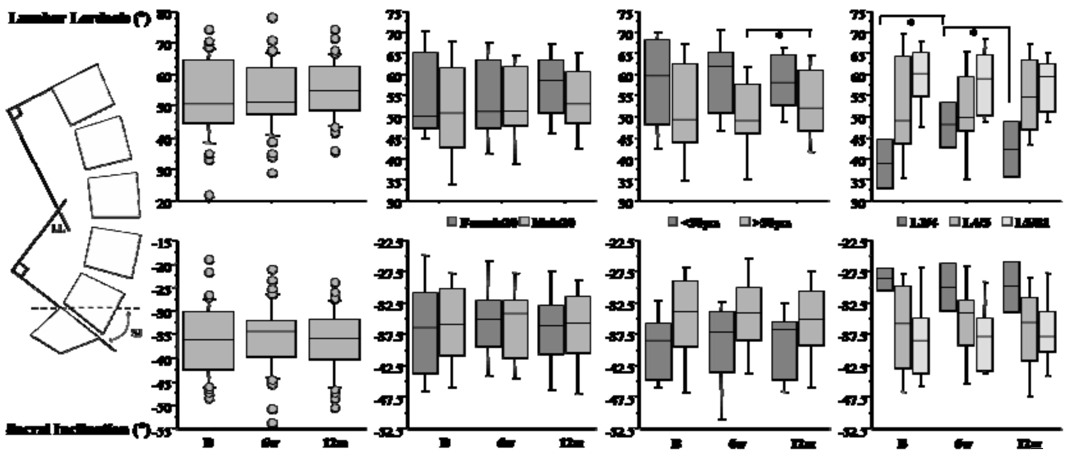


Figure 9.3: Box-plots representing the serial change in lumbar lordosis (LL) and sacral inclination (SI) for 40 cases that received lumbar surgery augmented with the DIAM interspinous implant and who had radiological data at all three time-points. Preoperative baseline and 6 week and 12 month postoperative time-points are presented. Statistically significant differences (shown by connectors; *$p<0.05$) were seen for LL in those older than 50 years (n=25) and in those who received their primary implant at L3/4 (n=2). No differences between genders, age groups or according to primary implant level were seen at either baseline or over time.

Sacral inclination (SI): Mean SI for the group was -35.4˚ (SD 7.5). The mean female preoperative SI was -35.6˚ (SD 9.0) while the men averaged -35.3˚ (SD 6.2) (NS). No difference in baseline SI for cases younger (-37.0; SD 8.2) or older than 50 years (-34.4; SD 6.9) was noted (NS). No difference existed between younger or older women (or men) (NS). No significant change to SI occurred when compared to preoperative baseline at either post-operative time-point (Table 9.1) or when all three time-points were analysed (Figure 9.3).

Primary disc angle (PDA): The mean disc angle at the primary level toward which treatment was directed was 9.8˚ (SD 6.1) preoperatively when all 62 cases were considered. The mean female preoperative PDA was 7.5˚ (5.2) while the men averaged 11.5 (SD 6.2); this difference between genders at baseline was significant ($p<0.01$). No difference in baseline PDA for cases younger (10.5˚; SD 6.6) or older than 50 years (9.3˚; SD 5.7) was noted. Paired comparisons of 59 cases revealed that PDA reduced by 2.2˚ ($p<0.0001$) from 9.8˚ (5.9) to 7.6˚ (SD 4.5) at six weeks postoperatively and remained reduced compared to baseline at 12 months ($p=0.03$). Serial comparisons (Scheffe) of the 40 cases with complete time-point data also indicated a significant postoperative flattening of PDA between baseline and 6 weeks only (2.2˚; $p<0.01$). A significant difference was noted between baseline and 6 weeks in the female cases (n=20; $p<0.05$) and in those who received their primary implant at L4/5 (n=26; $p<0.01$). Younger cases (n=15) showed a flattening of PDA between baseline and 12 months postoperatively (3.7˚; $p<0.05$). Group, gender, age and segmental level results for PDA are presented in Figure 9.4. Primary disc angle had significantly reduced at six weeks postoperatively in patients implanted with a 10mm device (n=13; 3.7˚, $p<0.01$). Assessment of PDA according to anatomical categorisation did not reveal any significant changes over time. Cases with LSS had a reduced PDA between baseline and 6 weeks postoperatively (2.5˚; $p<0.05$). When LSS was separated to account for cases with foraminal or central stenosis, patients with foraminal stenosis (FS; n=22) had a flattened PDA at 6 weeks compared to baseline (2.9˚; $p<0.01$); those with central canal stenosis (CS; n=5), DS (n=10), and FJPS (n=3) were no different at either postoperative time-point compared to baseline. Box-plots representing PDA in relation to device size, anatomical and diagnostic categorisations are illustrated in Figure 9.4.

Supradjacent disc angle (SDA): The mean baseline supradjacent disc angle was 10.0˚ (SD 4.7). The mean female preoperative SDA was 9.7˚ (5.1) while the men averaged 10.3 (SD 4.5) (NS). No difference in baseline SDA for cases younger (10.1˚; SD 4.4) or older than 50 years (10.0˚; SD 5.0) was noted (NS). There was no significant change to SDA over the period of observation for the group of 40 cases, however older subjects (n=25) had an increased SDA between 6 weeks and 12 months (2.0˚; $p<0.05$) based on serial comparisons (Figure 9.4).

Regional sagittal balance (RSB): The mean baseline RSB was 3.8mm (SD 40.2). Mean female preoperative RSB was 7.3 (38.1) while the men averaged 1.2 (SD 42.1). No difference in baseline RSB for cases younger (1.5; SD 41.8) or older than 50 years (5.4; SD 39.6) was noted (NS). No change to RSB occurred over time. RSB results are presented in Figure 9.6.

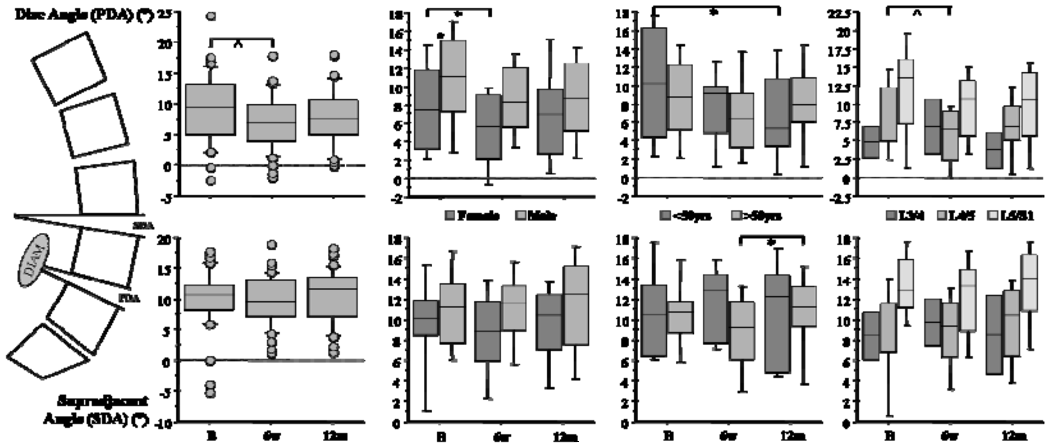


Figure 9.4: Box-plots representing the serial change in primary disc angle (PDA) and supradjacent disc angle (SDA) for 40 cases who received lumbar surgery augmented with the DIAM interspinous implant and who had radiological data at all three time-points. Preoperative baseline and 6 week and 12 month postoperative time-points are presented. For PDA, statistically significant differences (shown by connectors; *p<0.05; ^p<0.01) were seen (from left to right) in the initial 6 postoperative weeks (n=40), between genders at baseline (F27, M35), in females, and in those implanted at L4/5. Younger cases had a reduced PDA at 1 year compared to baseline. A 2.0˚ (p<0.05) increase in SDA in the older cases was seen between 6 weeks and a year.

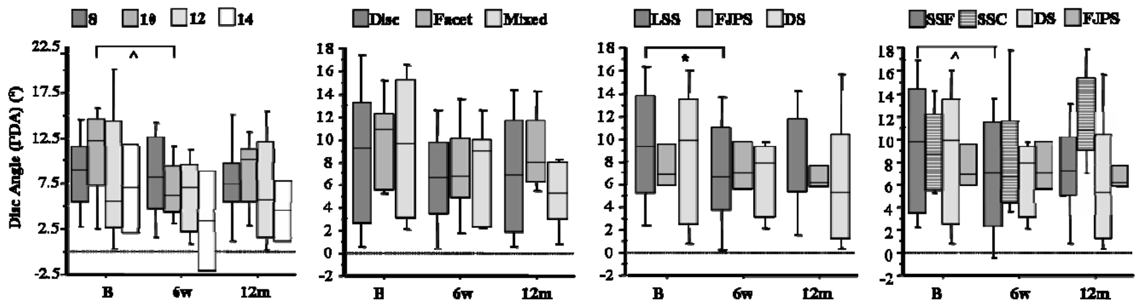


Figure 9.5: Box-plots representing the serial change in primary disc angle (PDA) according to: DIAM size [8mm n=14; 10mm n=13; 12mm n=11; 14mm n=2]; anatomical [disc n=19, facet n=16, mixed segment n=5 disease]; and diagnostic categorisation [spinal stenosis (LSS; n=27): foraminal (SSF; n=22) & central canal (SSC; n=5)], degenerative spondylolisthesis (DS; n=10), and facet joint pain syndrome (FJPS; n=3) for 40 cases who received lumbar surgery augmented with the DIAM interspinous implant and who had radiological data at all three time-points. Preoperative baseline, 6 week and 12 month postoperative time-points are presented. A significant flattening of the DA between baseline and 6 weeks was noted for cases implanted with a 10mm device and in patients with LSS (2.5˚; *p<0.05), and more specifically for those with SSF (2.9˚; ^p<0.01).

Relative sagittal balance (RRSB): The mean baseline RRSB was 0.02 (SD 0.13). Mean female preoperative RRSB was 0.04 (0.15) while the men averaged 0.01 (SD 0.12) (NS). No difference in baseline RRSB for cases younger (0.01; SD 0.13) or older than 50 years (0.03; SD 0.14) was noted (NS). No change to RRSB occurred over time. RRSB results are presented in 9.6.

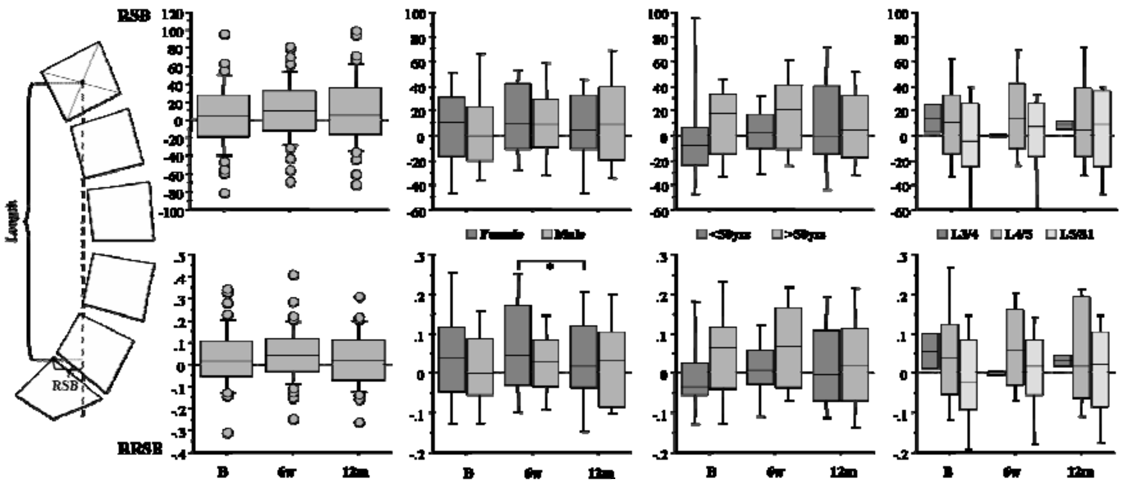


Figure 9.6: Box-plots representing the serial change in regional sagittal balance (RSB) and RSB normalised for the length of the lumbar spine (RRSB) for 40 cases who received lumbar surgery augmented with the DIAM interspinous implant and who had radiological data at all three time-points. Preoperative baseline and 6 week and 12 month postoperative time-points are presented. No significant difference was seen for either variable over time or between genders, age groups or implant levels.

Radius of curvature (RoC): The mean baseline RoC calculated between L1 and S1 (RoC1-6) was 420.0 (SD 202.5). There was a significant difference between the mean female preoperative RoC1-6 of 346.1 (158.9) and the male average of 477.0 (SD 215.8) (p=0.01). No difference in baseline RoC1-6 for cases younger (451.7; SD 198.4) or older than 50 years (398.6; SD 205.1) was noted (NS) or according to implant level. No serial change to RoC1-6 was detected. Results for RoC1-6 are presented using box-plots in Figure 9.7.

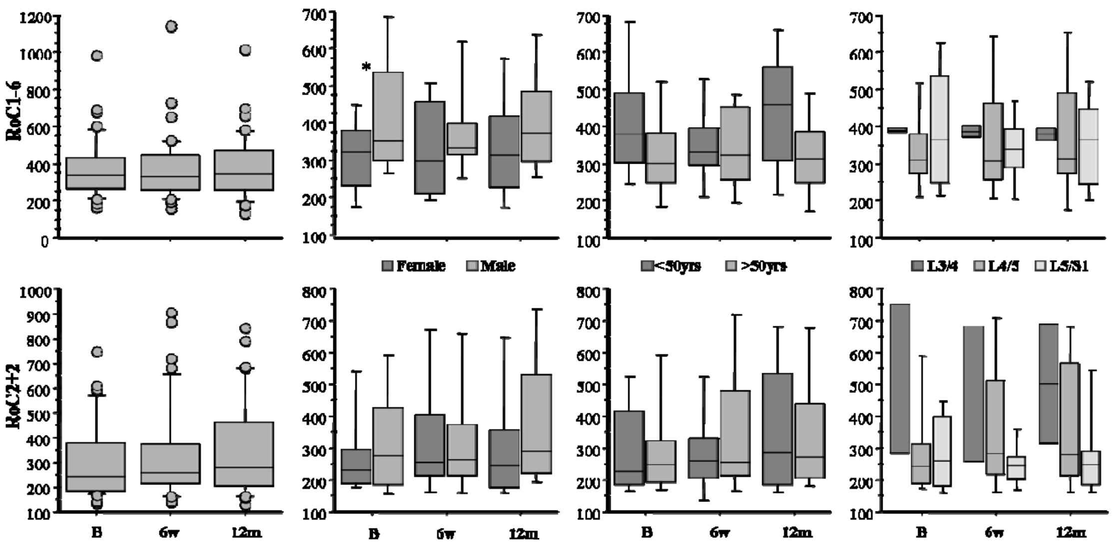


Figure 9.7: Box-plots representing the serial change in regional (RoC1-6) and local (RoC2+2) radius of curvature for 40 cases who received lumbar surgery augmented with the DIAM interspinous implant and who had radiological data at all three time-points. Preoperative baseline and 6 week and 12 month postoperative time-points are presented. Women had a smaller RoC1-6 at baseline, indicating greater lumbar regional curve (p<0.05). No significant difference was seen for either variable over time or between age groups or implant levels.

The mean baseline RoC local to the primary DIAM implant (RoC2+2) was 310.2 (SD 153.0). Female preoperative RoC2+2 was 295.5 (151.3) and the male average was 321.6 (SD 155.4) (NS). No difference in baseline RoC2+2 for cases younger (304.2; SD 154.7) or older than 50 years (314.3; SD 153.8) was noted or according to implant level. No serial change to RoC2+2 were observed over the year of observation (Figure 9.7). Results for each radiographic variable according to the number of DIAMs implanted during surgery revealed no differences over time for any variable other than primary disc angle (Figure 9.8). Primary disc angle for the 22 cases who received a single DIAM implant at surgery is presented in Figure 9.9 according to gender, age and primary implant level. This subset of results revealed a significant flattening of the disc angle at 6 weeks (by 2.7˚; p=0.01) and 12 months (by 2.4˚; p=0.03) compared to baseline.

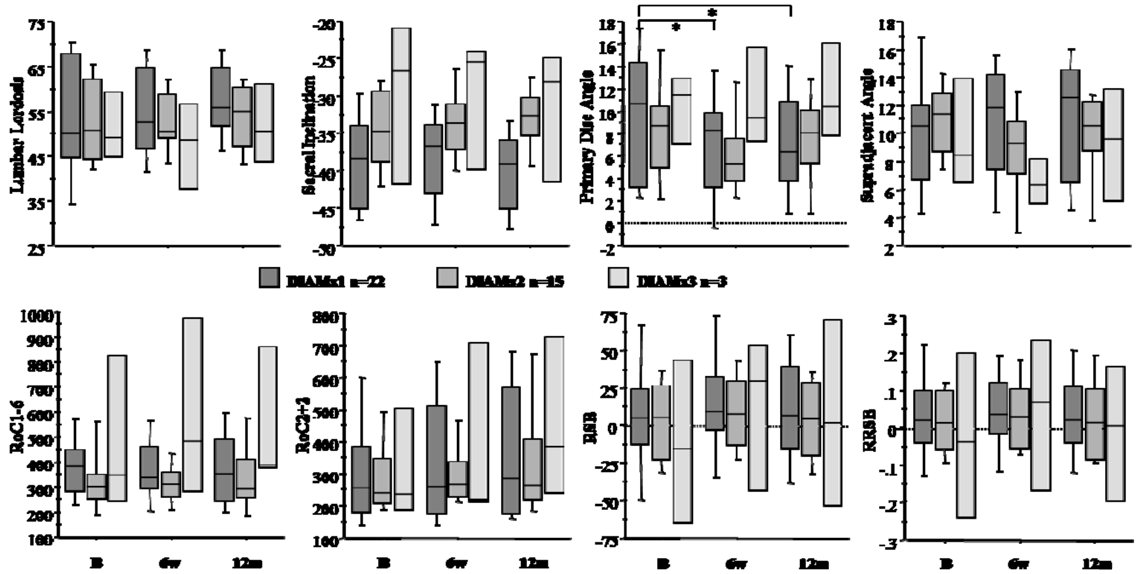


Figure 9.8: Box-plots representing the serial change for all tested radiographic variables according to the number of DIAMs (1 n=22; 2 n=15; 3 n=3) implanted during surgery for the 40 cases where all time-point data was available. Significant changes with time in primary disc angle (PDA) were detected in those receiving a single implant [*p<0.05].

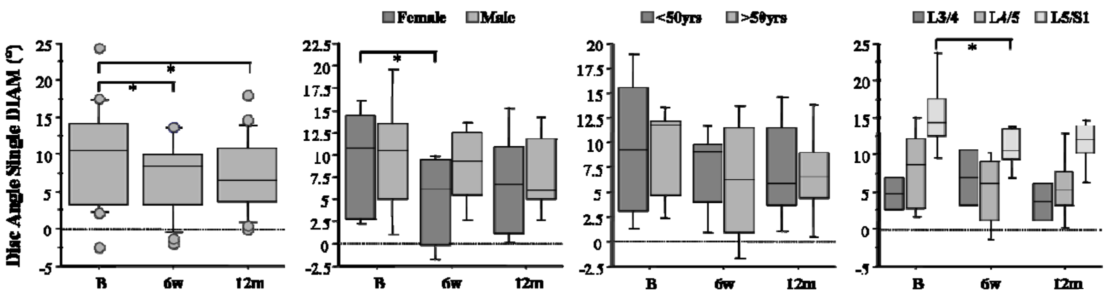


Figure 9.9: Box-plots representing the serial change over a year for primary disc angle (PDA) for the 22 cases that received lumbar surgery augmented with a single DIAM at the index level. Significant differences compared to baseline at both postoperative time-points were noted. Female cases and those with surgery directed at L5/S1 had a significantly reduced PDA at 6 weeks compared to baseline (p<0.05).

Relationships between variables at preoperative baseline:

Correlations between skeletal variables obtained at preoperative baseline for the 40 cases for which all time-point data were available are presented in Table 9.2. A strong relationship between RSB and RRSB was noted ($p<0.001$). Moderate relationships between: LL and SI, LL and PDA, LL and SDA, PDA and SDA, PDA and RSB, PDA and RRSB, and RoC1-6 and RoC2+2 existed ($p<0.001$). Weak relationships were found between: LL and RSB, and SI and RRSB ($p<0.05$).

Table 9.2: Matrix representing correlations [r-values] between all skeletal variables at baseline as assessed via standing lateral plain radiography in 40 cases that received decompressive lumbar surgery augmented with DIAM interspinous implant. Relationships ($p<0.05$) are indicated in bold.

	SI	**PDA**	**SDA**	**RSB**	**RRSB**	**RoC1-6**	**RoC2+2**
LL	-0.62[3]	0.48[2]	0.54[3]	-0.33[1]	-0.29	-0.16	-0.26
SI		-0.20	-0.17	-0.30	-0.33[1]	0.24	0.28
PDA			0.40[2]	-0.56[3]	-0.56[3]	0.21	-0.16
SDA				-0.27	-0.26	-0.09	-0.14
RSB					0.95[3]	-0.20	0.06
RRSB						-0.27	0.02
RoC1-6							0.65[3]

Statistically significant relationship: [1]$p<0.05$; [2]$p<0.01$; [3]$p<0.001$

Relationships between variables to according change between time-points:

Correlations for change between six weeks and baseline and 12 months and baseline for the 40 cases for which all time-point data were available are presented in Table 9.3. A strong relationship occurred between changes in LL and SI over a year ($r=0.7$; $p<0.001$). Moderate relationships were detected between the 6 week and baseline time-points for: LL and SI, LL and DA, LL and SDA, LL and RSB, LL and RoC2+2, DA and RSB, DA and RoC2+2, and RSB and RoC2+2. Weak relationships were found between: SI and DA, SDA and RSB, and SDA and RoC2+2. Moderate relationships were detected between the 12 months and baseline time-points for: LL and DA, LL and SDA, LL and RSB, LL and RoC2+2, DA and RSB, SDA and RSB, and SDA and RoC2+2. A weak relationship was seen between DA and RoC2+2.

9.4 Discussion

A surgical treatment alternative for lumbar degenerative pathologies is the interspinous implant, of which the DIAM is one example. The purported effect of all ISP devices is the introduction of a minor relative kyphosis at the index segment, where the anatomical impact is distraction of the interspinous space by stretching local soft tissues including the ligamentum flavum, facet joint capsules, posterior longitudinal ligament and posterior disc anulus (Christie et al. 2005).

Table 9.3: Matrix representing relationships [r-values] between all skeletal variables according to change between time-points in 40 cases who received decompressive lumbar surgery augmented with DIAM interspinous implant. The upper right triangle of values outlines the relationships between change in each variable between the six-week and preoperative time-points. The bottom left triangle outlines the relationships between changes in each variable at 12 months compared to baseline. RRSB was not included in this analysis.

				6weeks-Baseline			
12m-B	**LL**	**SI**	**PDA**	**SDA**	**RSB**	**RoC1-6**	**RoC2+2**
LL		-0.65[3]	0.49[2]	0.57[3]	-0.69[3]	0.00	-0.64[3]
SI	-0.70[3]		-0.32[1]	-0.15	0.20	-0.16	0.16
PDA	0.40[1]	-0.20		-0.03	-0.52[3]	0.09	-0.47[2]
SDA	0.64[3]	-0.23	0.27		-0.38[1]	-0.05	-0.39[1]
RSB	-0.44[2]	0.06	-0.52[3]	-0.42[2]		0.04	0.53[3]
RoC1-6	0.07	-0.02	0.02	0.03	-0.13		0.46[2]
RoC2+2	-0.50[3]	0.05	-0.32[1]	-0.45[2]	0.24	0.25	

Statistically significant relationship: [1]$p<0.05$; [2]$p<0.01$; [3]$p<0.001$

As previously reviewed in Chapter 2 (Crawford et al. 2009c), the mechanical effect is: enlargement of the central spinal canal, lateral recess and intervertebral foramen (Richards et al. 2005; Siddiqui et al. 2005; Siddiqui et al. 2006a); off-loaded zygapophysial joints (Wiseman et al. 2005); increased posterior disc height and reduced posterior intradiscal pressure (Swanson et al. 2003; Wilke et al. 2008). This has been shown to be particularly so in positions of lumbar extension (Lindsey et al. 2003; Swanson et al. 2003; Wilke et al. 2008) where infolding of the ligamentum flavum and posterior disc may result in neural tissue compromise (Willen et al. 1997; Chung et al. 2000; Kosaka et al. 2007). Evidence is generally based on ex vivo investigations, with few reports on skeletal changes seen in patients. The present investigation aimed to contribute to improving the understanding of the mechanical influence on the skeletal lumbar spine, of the DIAM in vivo.

Lumbar Regional Change:

The results of the present study have shown that for the 40 cases with all three time-point data, lumbar surgery augmented with the DIAM interspinous implant has no significant effect on skeletal: LL, SI, SDA, RSB, RRSB, RoC1-6 or RoC2+2. This confirmed the study hypothesis suggesting no change to regional skeletal curvature would occur after lumbar surgery augmented with the DIAM.

These results appear to be in agreement with the findings of Kim et al (2007) who used radiographic images taken with the patient in prone to assess their cohort of 31 cases receiving decompression surgery augmented with a DIAM. As such, comparisons with the results of the present investigation are made cautiously. Kim et al (2007) revealed an increase in mean lordosis (segmental Cobb inclusive of adjacent vertebra) of 1.2˚ (±0.24; ratio range 0.97-1.45˚) at the index segment in the presence of a DIAM; however this change was not statistically significant. They compared their DIAM cohort to patients who had received microdiscectomy alone and concluded that the increased segmental lordosis they observed in their microdiscectomy cases postoperatively (2.7˚ ±0.54; ratio range 2.1-3.2˚), did not occur for their DIAM-augmented cases. However, the value of the comparison between this and the present study is questionable given the dissimilar methods employed between the two studies. Kim et al (2007) acknowledged that standing lateral radiographs would represent more suitable imaging of sagittal alignment parameters in vivo for assessing the effect of DIAM surgery.

Segmental Disc Angle Change:

The only variable that significantly changed over time in the present study was the angulation of the primary disc (PDA). The mean PDA reduced by 2.2˚ at 6 weeks compared to baseline ($p<0.01$) in the 40 cases with all time-point data. On average, PDA reverted back to preoperative angulation by the 12-month follow-up time-point. This result confirmed the hypothesis that an early small relative kyphosis would occur in disc angulation at the index segment after DIAM-augmented surgery. Whether the 2.2˚ early PDA flattening constitutes a clinically meaningful change, requires consideration alongside patient-reported pain and function (reported in Chapter 10) and in light of the repeatability results for the method employed where a 0.5˚ (SD 1.1˚) mean difference was found for PDA (refer to Table 3.1). Although a group (n=40) mean flattening of 2.2˚ was detected, individual change may not be related to the surgery but rather to measurement error.

The finding of an early reduction in PDA appears to be in agreement with the study of Sobottke et al (2009) who assessed the effect on skeletal alignment via plain radiography in patients implanted with the X-Stop, DIAM or Wallis interspinous implants. They reported a mean 4.9˚ (SD 3.7˚; $p<0.0001$) flattening of the index disc angle at an average of 4 days (±22; range 1-29) postoperatively. At around the 6-week (202 ± 232 days) and 17-month (572 ± 377days) postoperative time-points, the early kyphosis was shown to revert by 2˚ (SD 3.1) and a further 1˚ (SD not reported) respectively, toward the preoperative angle, despite remaining significantly flatter (by 2˚; $p<0.05$). When considered on their own, the 33 DIAM patients reported by Sobottke et al (2009) had a preoperative PDA of 8.3˚ (SD 5.0˚), which reduced by 3.8˚ initially to a mean angle of 4.5˚, to then return to 3.1˚ by around the 6 weeks postoperative mark. This reflects a 5.2˚ relative kyphosis at the index level at 6 weeks postoperatively, which indicates more flattening than that evidenced in the present study where 2˚ reduction was noted. The X-

Stop patients in Sobottke et al's (2009) study flattened more than the DIAM cases (-3.8˚) initially ($p<0.05$).

To date, the X-Stop implant has been the most thoroughly examined of all the ISP devices. The early segmental flattening in excess of 5˚, reported for the X-Stop patients by Sobottke et al (2009), appears higher than that previously indicated for X-Stop cases in vivo (Anderson et al. 2006; Siddiqui et al. 2006b). One investigation revealed a change in angulation of between 1˚ to 2˚ at 6 months postoperatively, for both the lumbosacral and intervertebral disc angles using positional MRI (Siddiqui et al. 2006b). Another reported no change in lordosis angulation over a 2 year period as measured from erect radiography (Anderson et al. 2006). Given the early reversion back to baseline values evidenced beyond 6 weeks postoperatively in both the present study and that by Sobottke et al (2009), we speculate that the insignificant segmental change noted by Anderson et al (2006) and Siddiqui et al (2006b) was a reflection of their later follow-up, which may have missed any early segmental effect. Extending the same rationale to comparing the degree of index disc flattening noted between the present study and that reported by Sobottke et al (2009), the more dramatic reduction noted by the latter investigators may have been related to their earlier time-point used in assessment (4 days versus 6 weeks postoperatively). In combination, the results of the present study and those revealed by Sobottke et al (2009) suggest a surgically induced relative kyphosis at the index segment in the presence of a DIAM in vivo. Early change reverts back to preoperative angulation, somewhere around the one year postoperative mark.

Rohlmann et al (2005) reported a decreased mean disc angulation at the index segment (L3/4) from 4˚ to 1.2˚ (change of 2.8˚) in their study employing finite element modelling to test the effect of an interspinous implant (based on X-Stop properties) on lumbar spine loads. The reduction to PDA shown in the present study appears in agreement with this finding. Rohlmann et al concluded that implant forces were strongly influenced by the height of the implant and negligibly by its elastic modulus, while implant size and stiffness had only a minor effect on intradiscal pressure (Rohlmann et al. 2005). When the serial results for PDA (40 cases) in the present investigation were split by the size of the implant, only those implanted with a 10mm device ($n=13$) had a significantly reduced lordosis (3.7˚, $p<0.01$). This counterintuitive result may be spurious given that the limited subset of cases may have also been affected by potential confounders like gender or implant level. Also, the size of the device used by the surgeon relates more to the individual's anatomy and technical peri-operative sizing procedure, than a choice based on a desired segmental angulation outcome. What might be more relevant is whether any relationships exist between an individual's interspinous distance in loading preoperatively, the size of the implanted ISP after the sizing procedure, and their combined effect on patient reported pain and function. Rohlmann et al (2005) reported that the relationship between device size and pre-implantation interspinous distance was significant for the applied distraction force and subsequent implant loading force, when the implant size exceeded the interspinous distance (at a degenerated disc) by more than 6mm. Barbagallo et al (2009) have recently proposed using a classification system to preoperatively identify anatomical variations in spinous processes in order to mitigate surgical complications. Case studies reporting spinous process erosion secondary to stress-shielding (Miller et al. 2010), spinous process fracture (Barbagallo et al. 2009) and bilateral facet fracture (Chung et al. 2009) have been recently reported after ISP surgeries. Complications relating to surgery using interspinous implant are further discussed in the case illustration presented in Appendix XI.

When change to the index disc angulation was considered alone, the results of the present study (as illustrated in Figures 9.5&6) suggest that gender, age, segmental level, size of the implant and type of lumbar spinal stenosis, may influence the segmental effect. Female cases receiving either single or multiple DIAM implants showed reduced angulation at the index disc at 6 weeks, while male cases were unaffected. Younger cases from the main group of 40 with mixed pathologies had a flattened PDA at 12 months compared to baseline, while those with surgery applied to L4/5 had a reduced PDA at 6 weeks. Patients implanted with a single DIAM at L5/S1 had a reduced lordosis at the index disc at 6 weeks after surgery. When the 27 cases with LSS were split according to a predominant foraminal (n=22) or central canal (n=5) presentation, reduction of PDA was only noted for the former. It is difficult to draw conclusions based on these findings given the subset analyses have diminished group numbers, thereby weakening the statistical power of the results. It is proposed however that these trends might be considered for future studies, which should seek to explore subset populations within patient groups that are typically more broadly categorised (like lumbar spinal stenosis). This approach may serve to better understand the influence of the DIAM on skeletal curvature.

Sobottke et al (2009) did not include specific information regarding the demographic or clinical breakdown of their DIAM cohort, which were instead broadly described as having LSS within an undifferentiated wider group receiving ISP surgery using one of three devices. It is possible that their use of lateral radiography and focus on skeletal variables centring on the region of the intervertebral foramen, better enabled comment on the effect of DIAM on foraminal stenosis rather than stenosis affecting the central spinal canal. Sobottke et al (2009) suggested that their results be extrapolated to include a widening of the central canal based on other studies that have assessed ISP influence on foraminal and central canal stenosis (Richards et al. 2005; Siddiqui et al. 2006a). Anatomically, foraminal and central canal stenosis represent different pathologies, with probable differences in their clinical presentation. It might be expected that patients with foraminal stenosis present with predominant radicular leg symptoms, while central canal stenotic patients have a back pain emphasis. Sobottke et al (2009) observed VAS over the same period as skeletal variables after ISP surgeries and reported a weak and clinically questionable correlation ($r=0.33$; $p<0.05$) between change in pain and change in foraminal area. They did not reveal whether the pain related to the back or leg, so it is difficult to apply their results further to differentiate clinical guidelines. It is the opinion of the author that foraminal and central canal stenosis be considered separately in future research assessing ISP devices. This approach may improve the prediction of appropriate clinical pathways, although the generally poor correlation between the severity of radiographic changes and back pain may limit the clinical utility of radiographic outcomes (van Tulder et al. 1997; Djurasovic and Glassman 2007). Relationships between the radiographic and HRQoL findings for the present investigation are detailed in Chapter 10.

Whether induced flattening of the disc at the index segment after ISP surgery represents an undesirable degree of kyphosis is questionable. Based on the results of this study, where the supradjacent level was unaffected by the surgery, we speculate that any locally-induced change is isolated to the disc at the index segment alone and not borne elsewhere in the lumbar region. This may represent a satisfying result for the developers of the various ISP devices who initially aimed to provide a surgical alternative to fusion, to limit supradjacent segmental overload (Minns and Walsh 1997; Senegas 2002a; Taylor et al. 2007). On closer inspection of the line-chart for PDA in Figure 9.2, it can be seen that only two cases (of 40) flatten beyond parallel end-plates (into actual segmental kyphosis) at six weeks, but return back into a mild lordosis by one year postoperatively. The surgical technique guidelines for the use of the DIAM suggest that the device be implanted under fluoroscopic imaging to restrict distraction at the segment, in order to achieve no greater than parallel end-plates (Medtronic 2006). Based on the results of the present study where very few cases revealed a locally increased disc angle beyond parallel endplates, we suggest that fluoroscopic imaging is not necessary. The robustness of the supraspinous ligament as the confluence of the lumbodorsal fascia (Macintosh et al. 1986; Vaccaro et al. 2009), which is preserved in surgeries using DIAM or X-Stop devices, may naturally prevent over-distraction of the segment. Indeed, the one individual who began with their primary implanted level in kyphosis was apparently ‘corrected’ into lordosis from what may have been a preoperatively morbid angulation.

Regression of the radiological segmental changes toward preoperative values noted in this study and that of Sobottke et al (2009), suggest a potential for loss of ‘correction’ over time. Whether this change relates to a settling of the implant and/or the deformation fatigue properties of silicone cannot be answered by the present study, although their potential exists. The dynamic nature of the bone and periosteum that comprise the spinous processes, and the process involving postoperative tissue healing, may allow for a small degree of device settling, particularly subsequent to axial loading. The DIAM has been tested for its dynamic creep characteristics at loads in excess of that tolerated by bone; however no assessment has been made of its material response to serial loading at normal in vivo physiological levels (Taylor 2010). In a personal communication with the DIAM developer, who responded based on information provided by his bioengineer colleague, the indication was that <1mm of silicone fatigue deformation may be possible over a year (Taylor 2010). Speculatively, this may represent enough 'give' to fully explain regression of the PDA seen in the present and the Sobottke et al (2009) studies; irrespective of any contribution from device settling (see below). Of further interest in the latter investigation was that patients implanted with either the X-Stop or Wallis interspinous systems, also evidenced reduced correction at 1 year after an initial flattening, greater than seen for the DIAM. As reviewed in Chapter 2, these other two ISP alternatives are comprised of non-compressible materials (titanium/PEEK and PEEK, respectively) (Table 2.3), which may have less capacity to deform compared to the DIAM. Additionally, Rohlmann et al (2005) reported negligible influence of the elastic modulus of an implant on its intrinsic load-bearing forces based on finite element modelling with the X-Stop used as the basis. By this rationale, the loss of correction over time noted in the present study is speculatively more likely to be a consequence of device settling, than silicone deformation fatigue. This line of enquiry warrants further investigation in order to better appreciate the mechanical properties of the DIAM over an extended period. Whether any steps or technique modifications can be introduced to mitigate the potential problem of device settling, may be relevant given the aim of treatments for back pain are a sustained palliative effect that exceeds what might be expected for the natural history of the pathology (Dworkin et al. 2008; Deyo and Mirza 2009). Interestingly, the third-generation Superion ISP (Table 2.2) has been biomechanically tested in cadaveric specimens under extreme coupled loads aimed at determining the potential for device migration or damage (Goyal et al. 2008). Their results showed no device migration or subsidence, which may be due to a combination of its titanium material and potential for maximally occupying the interspinous space based on no requirement for implantation tools. A similar biomechanical assessment in typical physiological conditions appears warranted for the DIAM.

Several investigations previously summarised in Table 2.4 indicate that the female skeletal lumbar lordosis is more prominent than that found in males [Chapter 2.3]. This was not reflected in the cohort studied in the present investigation, where skeletal curvature was measured using the modified Cobb technique referencing end-vertebra (L1&S1) (see Chapter 2.3). Interestingly however, the baseline results for radius of curvature in the present investigation showed a larger mean RoC in the male cases, which suggests a generally flatter lumbar shape, in agreement with the literature. The contrasting results for the two variables describing gender differences in regional lumbar curvature noted in the present study may represent superior measurement of curvature characteristics using the RoC technique (Singer et al. 1994; Goh et al. 2000). The advantages of using geometrical shape-based measurement techniques were outlined earlier in Chapter 2.3.

Relationships between variables:

As expected, RoC1-6 and RoC2+2 at baseline were moderately associated ($r=0.65$), reflecting similarity between a regionally and locally derived lumbar radii of curvature. A larger r-value may have been anticipated, although some difference between the two variables would be expected, given RoC1-6 references the ends of the regional curve and is therefore less sensitive to segmental change (previous paragraph). Significant change of angulation at the index disc as shown in this study, in the absence of any other alteration to curvature, suggests that RoC2+2 would be more sensitive than RoC1-6 to the potential surgical effects. However, RoC2+2 was unchanged over the period of observation, which arguably indicates that any segmental change isolated to the disc, is overshadowed with inclusion of vertebral levels above and below it.

When considered according to changes noted per variable at both time-point comparisons with baseline, decreasing RoC2+2 related moderately to increasing LL. This finding is satisfying based on the rationale described in the previous paragraph.

Moderate relationships were noted between lumbar lordosis and sacral inclination ($r=-0.62$; $p<0.001$), supradjacent disc angle ($r=0.54$; $p<0.001$) and primary disc angle ($r=0.48$; $p<0.01$). Lumbar lordosis may be regarded as the sum of each disc angle in the region (Stagnara 1982; Jackson and McManus 1994; Jackson and Hales 2000), and therefore the associations found are not surprising. Given the L5/S1 disc comprises the largest contribution to LL (Stagnara 1982), and that LL reported in the present study referenced the sacral base, it is perhaps more surprising that a stronger inverse association was not evident. The LSD for SI, as noted in the intrarater repeatability assessment presented in Table 3.1, was 4.36˚. This represented comparably more error than was noted for the measurement of a single disc angle (3.05˚) as defined by adjacent endplates. SI is also a variable referencing a single segment as defined by the angle between the sacral base and the horizontal, and therefore is dependent on the rater's identification of the sacral base alone, on radiographs. It appears that the sacral base was less precisely defined than the other end-plates in the region, which may have contributed to the variability reported for the SI and LL variables. Interestingly, when considered according to change between time-points, convincing associations were noted between LL and SI (6w-B $r=-0.65$, 12m-B $r=-70$; $p<0.001$).

Lafage et al (2008) report the pelvis to play a compensatory role in equalising sagittal balance. As such, a relationship between RSB and SI (as assessed in this investigation) might have been expected. However results presented in Tables 9.2&3 indicate this was not the case. Instead, the strongest relationship with RSB was PDA, at baseline ($r=0.56$; $p<0.001$) and according to noted change at both time-points ($r=0.52$; $p<0.001$). It may be argued that the wide variability reported for RSB between the cases studied (refer to Table 9.1), and the LSD noted for its measurement (Table 3.1), resulted in weakened associations than might have been expected. Associations reported by others to occur between the pelvis and sagittal balance (based on skeletal measurements), refers to measurements inclusive of pelvic anatomy and relative position (Jackson et al. 2000; Gardocki et al. 2002; Labelle et al. 2004; Labelle et al. 2008; Lafage et al. 2008; Mac-Thiong et al. 2008). Radiographic images measured in the present study did not include the necessary pelvic landmarks and therefore suitable measurements for comparison to other studies could not be made. When sagittal balance is a key variable in skeletal assessment of spinal curvature, it appears valuable to include the pelvis in imaging.

The strong relationship ($p<0.001$) noted between RSB and RRSB at baseline ($r=0.95$) is not surprising given the latter is dependent on the former in its calculation.

No significant variations according to age were noted for baseline values or over time when compared to preoperative values for each variable assessed. It might be speculated that the cohort for this investigation were on average too young (52 years) for any age-related changes to be detected when they are most noted in patients aged beyond 65 years (as described in Chapter 2). In the cohort of 40 cases serially assessed in this study, only seven cases were 65 years or older. It is probable that the fewer cases in the >50 age group had a limited effect on the skeletal variables measured. Twenty-five percent of Sobottke et al's (2009) overall cohort (three implant types) were younger than 50 years, while 48% were >65 years (mean age 61yrs ±16). They did not report the demographics of their DIAM cases in isolation but it is reasonable to assume that the Sobottke et al (2009) cases were older than those presented in the current study. Therefore comparisons between the two studies must be applied cautiously.

Inspection of Table 9.1 and Figure 9.3 reveal wide variability between cases compared to group mean values for regional sagittal balance. This was also noted for surface-derived RSB for the healthy volunteers reported in Chapter 5 and for surgical patients when surface RSB was measured using rasterstereography (as described in Chapter 8). As previously speculated, RSB and trunk inclination can be influenced by postural sway (explored further in Appendices VII.1-3). This normal physiological process was intentionally not constrained in this radiographic study in order to allow for the closest approximation to the routine clinical assessment environment. As such, the single instantaneously captured radiographic image can only reflect the moment the image is taken. Results presented in Chapter 5 show no significant change to RSB over 1-year and 2-year time-points compared to baseline in the series of 11 healthy cases, although there was a noted variability at 6 months into follow-up. The other potential influence on values obtained for sagittal balance from radiography is the reference to the vertical "plumbline" of the radiography process. It might be argued that a general assumption of film-edge verticality is employed, which itself relies on the entire imaging process to maintain an accurate vertical. This assumption is challenged in the study reported in Appendix IX, which revealed a 1º deviation from vertical within and between the fourteen radiography sites that patients had the choice of using in order to obtain their radiographic examination.

Difficulties with the repeatability in reporting serial thoracolumbar or regional sagittal balance in adults, who undergo lumbar surgeries that have the potential to alter alignment, are therefore of concern. The results of Appendix IX indicate that the verticality of the radiographic buckey setup could itself vary 1.25º from true plumbline. Additionally, the SD for RSB reported in Table 3.1 to indicate the measurement error in deriving RSB via the method employed in this study was 1.9mm. Also contributing to the measurement's complexity is that sagittal alignment varies significantly in adults (Roussouly et al. 2005; Vialle et al. 2005), with the range of normal being 25mm either side of the vertical (Jackson and McManus 1994; Jackson and Hales 2000; Jackson et al. 2000). Investigators have indicated that the primary radiographically derived skeletal parameter relating to patient-reported outcomes is spinal alignment with reference to the sagittal vertical axis (Kawakami et al. 2002; Labelle et al. 2004; Glassman et al. 2005a; Kim et al. 2006b; Djurasovic and Glassman 2007; Lafage et al. 2008). Yet Van Royen et al (1998) questioned the accuracy of sagittal balance as measured via erect lateral radiography because of the variability apportioned to physiological postural features like sway. Interestingly, Van Royen et al controlled for the position and fixation of the long-cassette film by using a radio-opaque plumbline in their serial radiographic images. Based on the findings of the study reported in Appendix IX, it appears advisable to adopt this protocol when assessing regional or thoracolumbar spinal balance in order to control for variation in inclinations of the trunk or the imaging system itself. This is likely to be routine protocol for surgery cases being assessed in tertiary centres. However, the diverse radiology sites used by patients in the present study represented a suboptimal arrangement for acquiring radiographic images for research, although this aspect of the methodology was beyond the author's control.

The lack of an intra-image reference to account for any magnification or scaling differences between the serial images that have been derived from various radiography sites represents a limitation of the methods employed in this investigation. Given the imaging analysis aspect of the main study was executed to reflect the typical clinical process adopted by the collaborating neurosurgeon, further steps to prevent system errors were beyond the control of the author. This known a priori limitation to the study was the basis for using the standardised procedural guidelines distributed to all involved centres (Appendix IV). It also motivated the study assessing radiographic verticality presented in Appendix IX. The decision to use angular variables (like LL, SI, DA and SDA) to describe serial change was made knowing that they would not be influenced by scaling. This factor might then be considered to represent an advantage of angular measurements over those requiring an element of distance (RSB, RoC) when the available method does not allow for acceptable controls.

9.5 Conclusions

Lumbar surgery augmented with the DIAM interspinous implant applied to patients with a variety of lumbar pathologies, had no significant effect on skeletal: regional lumbar lordosis, sacral inclination, the disc angle above the primary implanted segment, regional sagittal balance, or either radius of curvature for the region or curvature local to the primary implant. A small yet statistically significant reduction of the index disc angle occurred at six weeks postoperatively. This was not maintained at 12 months. Gender, age, spinal level, DIAM size and the presence of foraminal stenosis separately influenced change in the index disc angle. The clinical significance of the noted change in skeletal lumbar curvature in this study is questionable.

CHAPTER 10

Relationships between surface and skeletal curvature and patient-reported pain and function after lumbar surgery augmented with the DIAM

10.1 Introduction

This chapter describes interactions between patient reported pain and function, and surface and skeletal spinal curvature for the prospective cohort. Results already presented have separately shown that DIAM-augmented lumbar decompressive surgery in this single-centre patient group resulted in: clinically important improvement in patient-reported back and leg pain and function (Chapter 7.1); early (6 weeks) reduction in the depth of the lumbar spine as assessed from the surface via rasterstereography (Chapter 7.2); early reduction in skeletal disc angle at the index level (Chapter 7.3); and no change in surface or skeletal curvature at one year after surgery compared to preoperative baseline values (Chapters 7.2&7.3). Whether preoperative or early postoperative changes in spinal curvature offered the capacity to predict response to the surgery at one year, was considered an important aspect of defining patient selection criteria and prognostic determinants for lumbar surgery augmented with the DIAM interspinous implant.

<u>10.1.1 HRQoL and surface spinal curvature</u>

No investigation has assessed spinal curvature or posture, as determined by measurements from the skin surface, for cases receiving interspinous implant surgery using any of the available devices. As yet, the observation that patients become more comfortable and consequently stand up straighter after DIAM surgery (Malone 2007b; Popovic 2007; Taylor 2010), continues to be an anecdotal impression representing low level evidence. Considering this sense of spinal straightening secondary to improved comfort, it was felt that patients experiencing reduced pain and improved function may show reduced LL, LD and TK, with their SB approximating a more vertical alignment. However, given the results for rasterstereography described in Chapter 7.2 revealing no significant serial change in any surface curvature variable beyond 6 weeks postoperatively, and in testing the hypothesis that surface curvature would not change after DIAM augmented surgery, differences according to responder categories were not expected.

<u>10.1.2 HRQoL and skeletal spinal curvature</u>

Few investigations have reported in vivo radiographically-determined skeletal curvature with patient-reported pain and function after surgery involving DIAM (Kim et al. 2007; Kasis et al. 2008; Sobottke et al. 2009). Of these three studies, Sobottke et al are the only investigators to examine relationships between such variables, where they contrasted change in pain and foraminal cross-sectional area (CSA) at the index level. No association was shown for their 33 DIAM cases despite separately describing clinically important reduction in VAS and an early flattening of the disc angle at the index segment. However, Sobottke et al described a weak relationship between pain and CSA ($r=0.33$; $p<0.05$) when the data for 129 cases who received either the DIAM (n=33), X-Stop (n=78) or Wallis (18) implants, were pooled. This result may be spurious given the opportunity for Type I error in assuming homogeneity in a sample who essentially received different interventions. Although the present investigation did not measure foraminal CSA due to concerns with lateral x-ray distortion, this chapter sought to examine whether skeletal curvature changes were related to patient reported pain (back and leg) or function. Primary disc angle (PDA) was the variable that was shown to flatten significantly by six weeks postoperatively in the first postoperative year of the present study (Chapter 7.3). Therefore, PDA was compared with response in pain and function, to test for interactions. It was anticipated that responders would show a flattened PDA based on the premise that the therapeutic aim of the DIAM purportedly distracted the posterior elements, thereby reducing neural tissue compromise (Taylor 2001; Taylor et al. 2007).

10.1.3 Surface and skeletal spinal curvature

Preliminary results of an initial 10 surgical cases from Phase II of the study were presented in Chapter 6, with results showing no association between surface (rasterstereography) and skeletal (radiography) lumbar lordosis at the pre- or 6 weeks postoperative time-points (Crawford et al. 2009b). Three studies (Appendices VIII.1, VIII.2 & VIII.3) were also undertaken as an adjunct to the main investigation, in order to explore the relationship between surface and skeletally-derived spinal curvature. The results of these studies indicated a weak relationship between surface and skeletal spinal curvatures in the lumbar spine (Appendix VIII.1), with the explanation for this putatively relating to vertebral morphology (Appendix VIII.2) and variable thickness of overlying skin tissues (Appendix VIII.3). Consequently, a weak association was expected between surface and skeletally-derived variables for spinal curvature in the larger cohort from the prospective series, for whom both sets of data were available.

10.2 Methods

A critical aspect for this chapter of the investigation was what constituted a responder. The terminologies and categories used to indicate the type of response according to MID recommendations were outlined in the HRQoL section of Chapter 3 (3.7.2). In summary, the change score calculated on the absolute difference between patient-reported values at two time-points is referred to as absolute change [e.g. 12m-B], while change normalised to the baseline value is referred to as normalised change [e.g. (12m-B)/B]. Responders were categorised according to change scores calculated from their one year postoperative time-point and their preoperative values. When absolute change scores were analysed, improvement was deemed of moderate clinical importance for function, back and leg pains when 30% or greater reduction in ODI (function) or VAS (back and leg pain) scores occurred (Dworkin et al. 2008; Ostelo et al. 2008). Reductions over 15% for ODI and 20% for VAS scores represented minimum acceptable change. Cases that changed less than these minimally acceptable values were categorised as non-responders. When normalised change scores were analysed, improvements in function, back and leg pains that were equal to, or in excess of 20% for VAS or ODI were considered minimally acceptable, while 30% or more improvement was recorded to be of moderate clinical significance. Distinction between these categories has been previously explained in Chapter 3. Cases who reported no pain or dysfunction both at baseline and the year postoperative time-point were excluded from responder analysis; this was only applicable in terms of leg pain scores. In all tests of statistical significance $p<0.05$ was established to represent a meaningful difference.

10.2.1 HRQoL and surface spinal curvature

Analyses of surface curvature in relation to responders for pain (back and leg) and function, were applied using the baseline (n=39), early change (6w compared to baseline; n=39) and serial (B, 6w, 6m, 12m; n=27) surface curvature values, for cases where patient-reported questionnaire and rasterstereographic data were available. Descriptive statistics split by responder category (moderate, minimal or non-responder) were used to report mean (SD) LL, LD, PI, TK, and SB. Comparisons between preoperative surface curvature and pain (back and leg) or function were made using Pearson's correlation coefficient [r-values]. Surface curvatures at baseline, and early change seen in the initial 6 weeks postoperatively, were assessed using unpaired t-tests. Each variable for surface curvature (LL, LD, TK and SB) was used as the dependent variable, with responder category as the nominal variable. Serial change in surface curvature for a year after surgery was assessed using Scheffe's post-hoc test, split according to pain or function response. Box-plots were employed to present these data.

10.2.2 HRQoL and skeletal spinal curvature

Analyses of skeletal curvature in relation to responders for pain (back and leg) and function, were applied using the baseline (n=59), early change (6w compared to baseline; n=59) and serial (B, 6w, 12m; n=40) skeletal curvature values, for cases where patient-reported questionnaire and radiographic data were available. Descriptive statistics split by responder category (moderate, minimal or non-responder) were used to report mean (SD) LL, PDA, SI, RSB and RoC (local to the DIAM implant) at baseline, and the change scores for each variable between baseline and six weeks. Comparisons between preoperative skeletal curvature and pain (back and leg) or function were made using Pearson's correlation coefficient [r-values]. Early change in primary disc angle (PDA) was assessed using an unpaired t-test, with PDA as the dependent variable, and responder category as the nominal variable. Serial change in PDA for a year after surgery was assessed using Scheffe's post-hoc test and split according to pain and function response. Box-plots were employed to present these data.

10.2.3 Surface and skeletal spinal curvature

Comparisons between values obtained for surface and skeletal spinal curvatures were made using Pearson's correlation coefficient for 33 cases for which both sets of data were available. Values at baseline and change scores between 6 weeks and baseline were compared to identify relationships. Significant associations are reported and presented as scatter-plots.

10.3 Results

Associations and results for the comparison of: HRQoL and surface spinal curvature; HRQoL and radiographically-derived skeletal curvature; and surface and skeletal spinal curvature are reported.

10.3.1 HRQoL and surface spinal curvature

Baseline comparisons (n=39): No differences between responders and non-responders in back pain, leg pain or function were detected in baseline surface curvature, for 39 cases scheduled to receive lumbar surgery augmented with DIAM. Baseline means (SD) for LL, LD, PI, TK, and SB are presented in Table 10.1, according to response by 12 months postoperatively.

Similarly, no correlation was noted between any surface curvature variable and back pain, leg pain or function (Table 10.2).

Early change in surface curvature [6 weeks; n=39]: When each surface curvature variable was assessed according to actual change in pain and function at 12 months, no differences were found between responder groups. In contrast, when the results were split according to normalised response, LL and TK showed a difference between back pain moderate-responders and non-responders. LL and TK results have been presented in Figures 10.1 and 10.2, respectively. Moderate normalised responders (n=30), showed a flattened LL at 6 weeks compared to baseline (by 3.4˚), which was significantly different from the non-responders (n=7) whose LL had increased at 6 weeks after surgery (by 3.0˚; $p<0.05$).

Similarly, TK reduced by 2.4˚ in moderate normalised back pain responders, reduced by 9.9˚ in minimal back pain responders, and increased by 1.6˚ in cases that did not respond according to back pain.

Table 10.1: Mean (SD) baseline values for surface curvature as determined using rasterstereography in 39 preoperative DIAM-augmented lumbar surgery patients who were imaged in standing in the clavicle position. Case numbers comprising each subgroup are indicated. Two cases were not included in the leg pain analysis, having had no leg pain preoperatively or at 12 months postoperatively. No differences were detected ($p<0.05$).

		Total	**Moderate**	**Minimal**	**Non**
Cases	Back	39	15	5	19
	Leg	37	16	4	17
	Function	39	8	8	23
Baseline					
Lumbar Lordosis (°)	Back	42.0 (11.3)	43.9 (12.2)	44.7 (12.0)	41.0 (9.7)
	Leg		41.2 (12.4)	41.0 (10.4)	43.0 (11.6)
	Function		37.8 (12.1)	41.8 (17.6)	43.6 (8.1)
Lumbar Depth (mm)	Back	54.2 (12.2)	53.2 (16.5)	54.4 (14.4)	55.0 (7.6)
	Leg		51.9 (11.7)	53.0 (15.1)	57.3 (12.7)
	Function		47.9 (15.9)	54.9 (15.2)	56.1 (9.2)
Pelvic Inclination (°)	Back	14.2 (7.3)	14.0 (6.9)	12.9 (13.9)	15.0 (5.7)
	Leg		14.2 (7.2)	16.2 (6.6)	13.7 (8.3)
	Function		10.2 (9.3)	16.4 (7.0)	14.9 (6.4)
Thoracic Kyphosis (°)	Back	62.6 (11.5)	65.9 (14.1)	60.5 (10.2)	61.0 (9.3)
	Leg		63.7 (8.7)	53.6 (11.5)	63.2 (13.8)
	Function		59.1 (9.4)	65.5 (14.4)	62.8 (11.2)
Sagittal Balance (mm)	Back	26.5 (26.8)	29.1 (27.0)	26.1 (12.6)	23.5 (30.7)
	Leg		33.3 (33.5)	20.7 (18.3)	19.3 (21.1)
	Function		24.8 (22.9)	31.2 (35.2)	25.4 (25.9)

Moderate responders included patients improving more than 30% for each variable. Minimal responders improved between 20 and 29% for pain and between 15 and 29% for function at 12 months compared to baseline (12m-B). Non-responders were defined as cases with less than minimal improvement (or deterioration) over the year of observation. Mean (SD) preoperative values for each surface curvature variable according to response in: Back=back pain (VAS); Leg=Leg pain (VAS); Function=ODI. No significant differences were noted between variables ($p<0.05$).

Table 10.2: Comparisons between preoperative surface curvature and self-reported back pain, leg pain and function, in 39 cases who were scheduled to receive lumbar surgery augmented with DIAM interspinous implant(s). No significant correlations were noted between variables.

	Back Pain (VAS)	**Leg Pain (VAS)**	**Function (ODI)**
Lumbar Lordosis (LL)	0.10	-0.21	-0.07
Lumbar Depth (LD)	-0.07	-0.30	-0.24
Pelvic Incidence (PI)	-0.11	-0.13	-0.17
Thoracic Kyphosis (TK)	0.18	-0.13	0.04
Sagittal Balance (SB)	-0.07	0.05	0.00

r-values

A moderate correlation was shown between early change in LL (between 6 weeks and baseline; LL 6w-B), and normalised back pain [(12m-B)/B] ($r=0.49$; $p<0.01$). No associations were shown between: LL 6w-B and absolute back pain response at a year ($r=0.31$; $p=0.05$); TK 6w-B and absolute back pain response ($r=0.31$; $p=0.05$); or TK 6w-B and absolute back pain response ($r=0.18$; $p=0.27$).

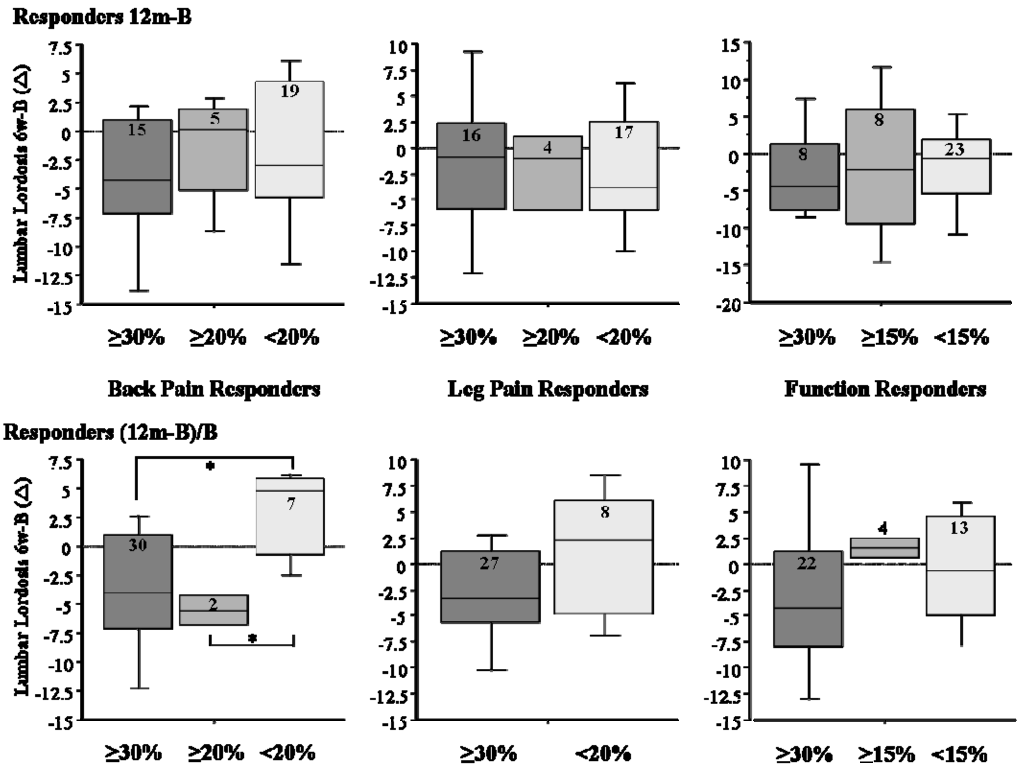


Figure 10.1: Change in surface lumbar lordosis as derived from rasterstereography between 6 weeks postoperatively and baseline, according to back pain (left), leg pain (middle), and function (right) response, as reported for 39 patients at 12 months after lumbar surgery augmented with DIAM. Case numbers related to each response group are indicated. Moderate (dark grey), minimal (medium grey) and non-responders (light grey) are shown. Absolute response at one year (12m-B) is presented in the top set of graphs, while response normalised for baseline values appears at the bottom. *Significant difference=$p<0.05$.

The results for LD change between baseline and 6 weeks (LD 6w-B) were significantly different ($p<0.05$) between minimal relative back pain responders (flattened by 9.7mm) and non-responders (flattened by 0.9mm). The reduction of 5.4mm in moderate back pain responders (≥30%) versus the non-responders (0.9mm) was not significantly different ($p=0.11$). No associations were noted between LD 6w-B and either relative or actual back pain response ($r=0.26$; $p=0.11$, $r=0.17$; $p=0.32$, respectively).

Serial change in surface curvature [B, 6w, 6m, 12m; n=27]: When surface curvature variables were assessed over the year of observation and split according to responders in leg pain or function, no differences were detected between responders for any variable. Analysis according to back pain response (presented in Figure 10.3) showed differences in LD, LL and TK between responder groups. When assessed in terms of actual back pain response, no change to LD occurred in moderate responders, while minimal improvers and non-responders showed an initial flattening followed by a progressive increase back to preoperative values. In terms of relative responders, moderate improvers showed an initial reduction in lumbar depth at 6 weeks, which returned to preoperative values increasingly by the year time-point. Additionally, LL had reduced by 6 weeks but remained unchanged compared to baseline at 6 and 12 months postoperatively. Corresponding case numbers per group in the serial analyses are indicated in Table 10.3. Figure 10.3 presents the serial results for LD, LL and TK according to actual (12m-B) and relative back pain (12m-B/B) response.

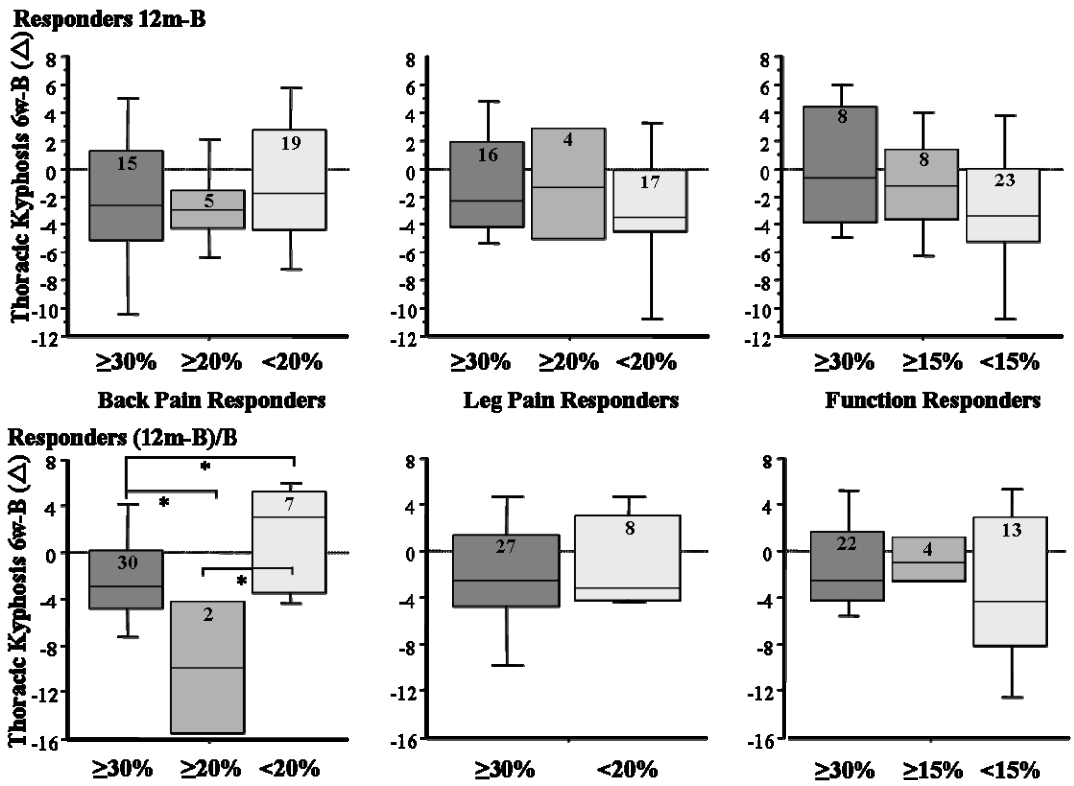


Figure 10.2: Change in surface thoracic kyphosis as derived from rasterstereography between 6 weeks postoperatively and baseline, according to back pain (left), leg pain (middle), and function (right) response, reported by 39 patients at 12 months after lumbar surgery augmented with DIAM. Case numbers related to each response group are indicated. Moderate (dark grey), minimal (medium grey) and non-responders (light grey) are shown. Absolute response at one year (12m-B) is presented in the top set of graphs, while response normalised for baseline values appears at the bottom. *Significant difference=p<0.05.

Table 10.3: Case numbers per responder group according to absolute (12m-B) and normalised [(12m-B)/B] back pain, leg pain and function, at 12 months. The proportion of moderate responders was greater when relative change in pain and function were reported.

Case numbers		**Moderate**	**Minimal**	**Non**	**Nil B**
Back Pain	12m-B	8	5	14	
	(12m-B)/B	21	1	5	
Leg Pain	12m-B	9	4	10	4
	(12m-B)/B	19	0	4	4
Function	12m-B	4	7	16	
	(12m-B)/B	17	3	7	

Moderate=moderate responder representing clinically important change; Minimal=minimal responder representing minimally acceptable change; Non=Non-responder; Nil B=No baseline or 12 months pain and therefore not assessed; 12m-B=Absolute change between 12 months and preoperative baseline; (12m-B)/B=Change normalised for baseline by one year postoperatively.

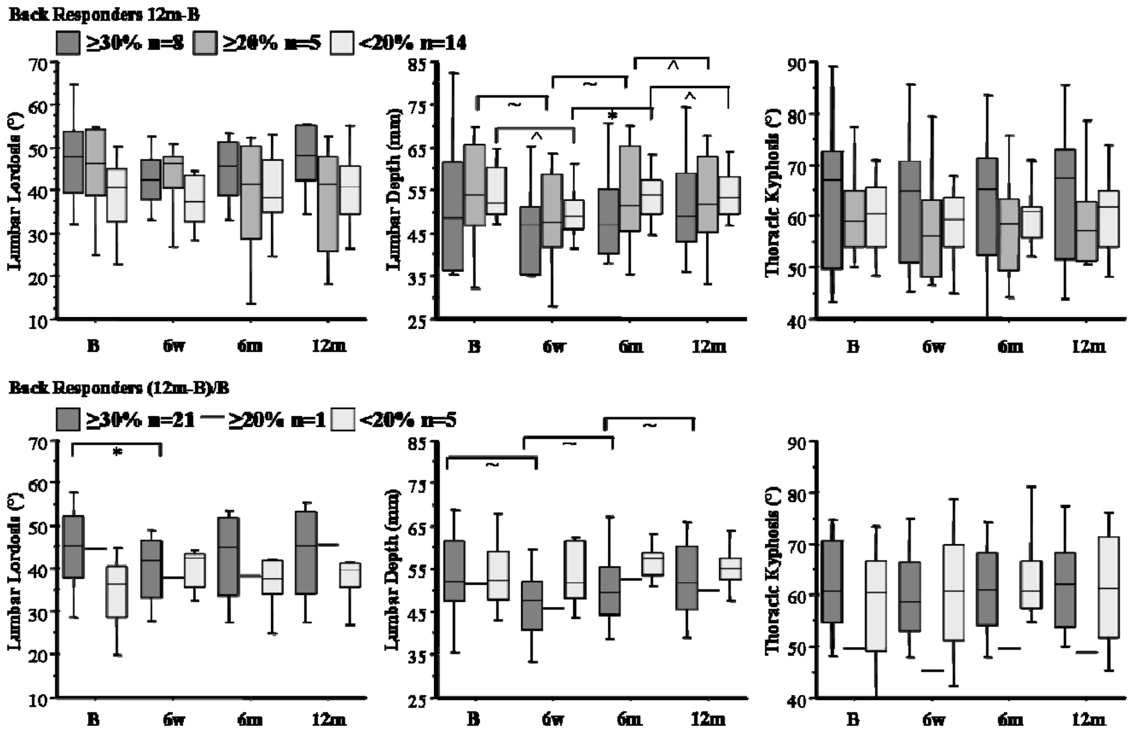


Figure 10.3: Box-plots showing serial change to LL (left), LD (middle) and TK (right) as determined from the skin surface via rasterstereography and according to back pain responder groups (absolute change: 12m-B; normalised change: (12m-B)/B). When referenced against change normalised baseline values, moderate improvers (n=21) showed reduced LD at 6 weeks, which returned to preoperative values by 12 months. Minimal (n=5) and non- responders (n=14) showed reduced LD by 6 weeks according to actual back pain response. Significant difference: *p<0.05, ^p<0.01, ~p<0.001.

10.3.2 HRQoL and skeletal spinal curvature

Baseline comparisons (n=59): When comparing mean values for skeletal curvature at baseline between responders and non-responders in actual back pain, leg pain or function, sagittal balance showed a difference between groups, in terms of back pain and function. Moderate back pain responders had a positive RSB [13.0 (41.3)], while non responders had a negative RSB on average [-8.7 (33.9); p<0.05]. Moderate responders in function had positive RSB [22.4 (40.3)], while non-responders had negative RSB at baseline [-5.3 (35.9); p<0.05]. The other skeletal curvature variables (LL, SI, PDA and RoC2+2) assessed in the 59 cases, showed no baseline differences between response groups. Baseline means (SD) for LL, PDA, SI, RSB and RoC2+2, are presented in Table 10.4 according to actual response by 12 months postoperatively (12m-B).

Weak correlation was noted at baseline between sagittal balance (RSB) and leg pain (r=0.31; p<0.05). No association was noted for any other surface curvature variable when baseline levels of patient-reported back pain, leg pain or function were considered (Table 10.5).

Early change in skeletal curvature [6w; n=59]: When each skeletal curvature variable was assessed for change between baseline and six weeks according to response by 12 months (Table 10.6), a difference was found for primary disc angle (PDA) between moderate responders and non-responders in back pain and function; no difference in leg pain response was noted.

Moderate absolute back pain responders (n=27), showed a small reduction in PDA of 1.0˚ (3.8) at 6 weeks compared to baseline, while non-responders (n=24) had a comparably larger reduction of 3.9˚ (3.4; p<0.01). In terms of functional improvements, moderate responders (n=15) had a flattened PDA of 1.2˚ (4.4), while the non-responder's (n=34) PDA reduced more [by 3.5˚ (3.1); p<0.05]. These results for PDA according to responders at 1 year postoperatively are presented in Figure 10.4. There were more responders (≥30% plus ≥20%) in terms of back (n=27+8) and leg pain (n=26+21) than responders according to function (n=15+10) (Table 10.6).

Table 10.4: Mean (SD) baseline values for skeletal curvature as determined using radiography in 59 DIAM-augmented lumbar surgery patients who were imaged in standing in the clavicle position at baseline. The numbers of cases comprising each subgroup are indicated. Moderate, minimal and non-responders according to actual improvements in back (B) and leg (L) pain and function (F) are presented. Sagittal balance was different at baseline between moderate and non-responders for back pain and function determined at one year postoperatively.

Case Numbers	**Total**	**Moderate**	**Minimal**	**Non**
Back Pain	59	27	8	24
Leg Pain	54	26	7	21
Function	59	15	10	34
Baseline				
Lumbar Lordosis (LL) (˚)	Back	51.2 (12.7)	55.3 (12.8)	53.5 (10.4)
	Leg	53.0 (12.7)	48.2 (11.1)	54.0 (11.4)
	Function	48.7 (12.6)	53.4 (9.4)	54.3 (11.7)
Primary Disc Angle (PDA) (˚)	Back	9.1 (5.8)	11.4 (4.6)	10.4 (6.9)
	Leg	9.2 (5.9)	9.5 (4.7)	11.6 (6.5)
	Function	7.9 (5.0)	8.9 (6.8)	11.1 (5.8)
Sacral Inclination (SI) (˚)	Back	-36.0 (7.2)	-37.7 (6.8)	-35.4 (6.6)
	Leg	-36.9 (6.8)	-34.2 (4.1)	-36.1 (7.1)
	Function	-35.3 (7.0)	-35.7 (8.3)	-36.3 (6.5)
Sagittal Balance (RSB)	Back	13.0 (41.3)	6.8 (47.4)	-8.7 (33.9)[1]
	Leg	6.8 (37.5)	20.9 (40.5)	-5.1 (40.7)
	Function	22.4 (40.3)	4.1 (46.3)	-5.3 (35.9)[1]
Radius of Curvature (RoC2+2)	Back	334 (310)	358 (177)	302 (144)
	Leg	340 (304)	385 (209)	305 (166)
	Function	445 (396)	217 (67)	303 (138)

Total=cases included in analysis (5 cases had no leg pain at baseline or 1 year and were therefore not included in analysis); Moderate=responders improving more than 30% for all variables; Minimal=responders improving between 20 and 29% for pain and between 15 and 29% for function; Non=non-responders with less than minimal improvement (or deterioration) over the year of observation; Mean (SD) preoperative values for each surface curvature variable according to response in back pain (VAS), leg pain (VAS) and function (ODI). Significant differences noted for RSB between moderate and non-responders [1]p<0.05.

Table 10.5: Comparisons between preoperative skeletal curvature and self-reported back pain, leg pain and function, in 59 cases who were scheduled to receive lumbar surgery augmented with DIAM interspinous implant(s). Weak association was noted between baseline sagittal balance and self-reported leg pain only.

	Back Pain (VAS)	**Leg Pain (VAS)**	**Function (ODI)**
Lumbar Lordosis (LL)	-0.13	-0.14	-0.14
Primary Disc Angle (PDA)	-0.20	-0.19	-0.17
Sacral Inclination (SI)	-0.01	-0.11	-0.02
Sagittal Balance (RSB)	0.24	0.31[1]	0.18
Radius of Curvature (RoC2+2)	0.10	0.11	0.17

r-values; [1]p<0.05

Table 10.6: Mean (SD) values for change to skeletal curvature at 6 weeks compared to baseline as determined using radiography in 59 DIAM-augmented lumbar surgery patients who were imaged in standing in the clavicle position. The number of cases comprising each subgroup is indicated. Moderate, minimal and non-responders according to actual improvements in back (B) and leg (L) pain and function (F) are presented.

Case Numbers	**Total**	**Moderate**	**Minimal**	**Non**
Back	59	27	8	24
Leg	54	26	7	21
Function	59	15	10	34
6 weeks – Baseline (△)				
Lumbar Lordosis (LL)	Back	1.2 (9.7)	-1.6 (5.4)	-2.1 (5.9)
	Leg	0.7 (10.1)	-0.4 (3.6)	-1.5 (5.4)
	Function	2.8 (13.2)	0.0 (3.0)	-2.2 (5.1)
Primary Disc Angle (PDA)	Back	-1.0 (3.8)	-2.2 (3.3)	-3.9 (3.4)[2]
	Leg	-1.8 (3.8)	-1.4 (2.1)	-3.9 (3.7)
	Function	-1.2 (4.4)	-0.2 (3.7)	-3.5 (3.1)[1]
Sacral Inclination (SI)	Back	-0.5 (4.7)	0.8 (3.3)	1.8 (3.8)
	Leg	-0.4 (3.9)	0.1 (4.2)	1.9 (4.4)
	Function	-0.9 (4.6)	-0.9 (3.5)	1.7 (4.1)
Sagittal Balance (RSB)	Back	3.7 (21.5)	5.9 (16.0)	10.1 (21.6)
	Leg	4.0 (22.8)	-1.4 (9.5)	10.2 (21.8)
	Function	-0.6 (27.1)	7.8 (14.0)	9.4 (19.0)
Radius of Curvature	Back	-1.2 (340)	23.5 (162)	21.2 (198)
	Leg	3.2 (375)	18.5 (178)	-4.2 (106)
	Function	-88.0 (415)	39.0 (114)	47.0 (204)

Total=cases included in analysis (5 cases had no leg pain at baseline or 1 year and were therefore not included in analysis); Moderate=responders improving more than 30% for all variables. Minimal=responders improving between 20 and 29% for pain and between 15 and 29% for function. Non=non-responders with less than minimal improvement (or deterioration) over the year of observation. Mean (SD) preoperative values for each surface curvature variable according to response in back pain (VAS), leg pain (VAS), and function (ODI). Significant differences noted for PDA between back pain moderate and non-responders [2]p<0.01 and function moderate and non-responders [1]p<0.05

Serial change in skeletal curvature [B, 6w, 12m; n=40]: When skeletal curvature variables were assessed over the year of observation and split according to change in back pain, leg pain or function between 12 months and baseline, non-responders showed a variously reduced PDA, while responders did not change. In terms of absolute back pain response, PDA reduced in the initial 6 weeks by 3.8˚ in non-responders (p<0.01). In terms of absolute leg pain response, PDA reduced by 3.0˚ in non-responders ($p<0.05$). In terms of absolute function response, non-responders had a reduced PDA by 3.6˚ ($p<0.001$) and 2.5˚ ($p<0.05$) at 6 weeks and 12 months compared to baseline, respectively. Non-responders in normalised for baseline function also showed a reduced PDA by 4.2˚ ($p<0.05$) at 6 weeks. Serial PDA for the first year of observation is presented in Figure 10.5.

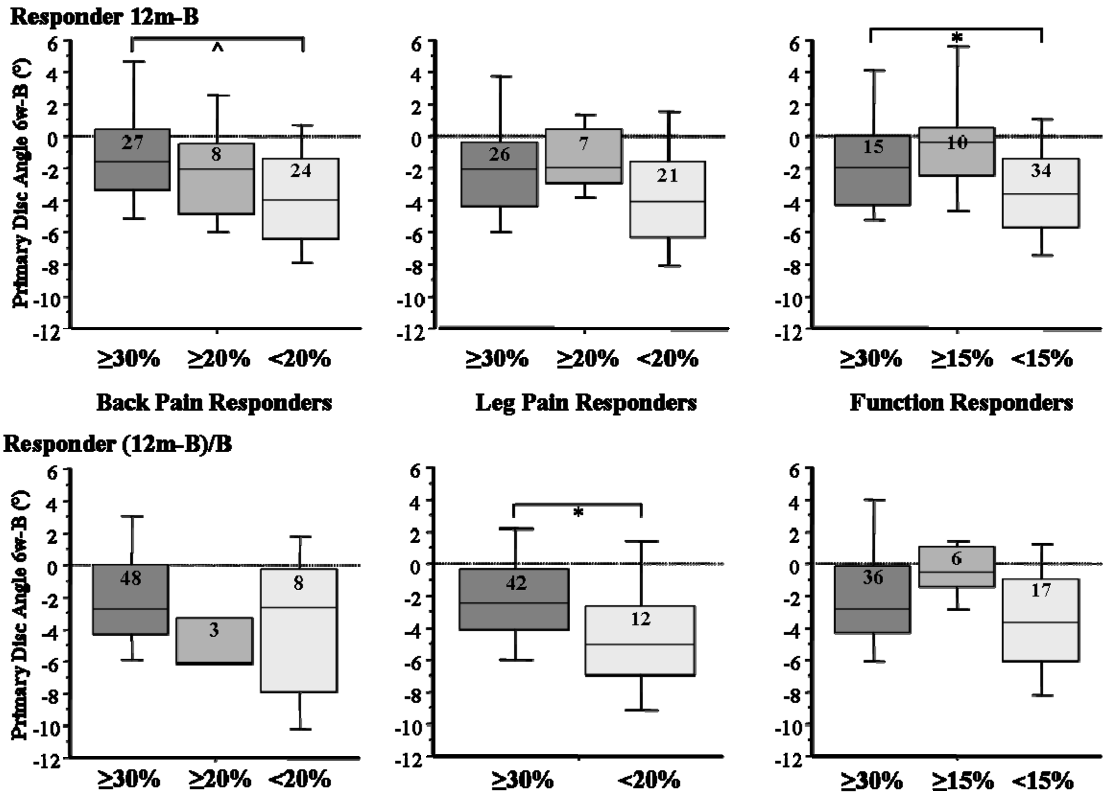


Figure 10.4: Change in skeletal primary disc angle (PDA) as derived from radiography between 6 weeks postoperatively and baseline, according to back pain (left), leg pain (middle), and function (right) response, as reported by 59 patients at 12 months after lumbar surgery augmented with DIAM. Case numbers related to each response group are indicated. Moderate (dark grey), minimal (medium grey), and non-responders (light grey) are included. Absolute response at one year (12m-B) is presented on the top row, normalised response at one year [(12m-B)/B] on the bottom row. Significant differences are shown: *$p<0.05$; ^$p<0.01$.

Results for serial RSB in the first year of follow-up also revealed significant change in non-responders, while responders were unchanged. According to absolute back pain response (12m-B), non-responders showed an initial (by 6 weeks) increase in RSB by a mean of 11 (approximate mm), followed by a decrease at 12 months back to baseline levels ($p<0.05$).

According to absolute function response (12m-B), non-responders showed an increased RSB by a mean of 10.6 ($p<0.05$). In terms of function normalised for baseline response [(12m-B)/B], non-responders showed a decreasing RSB between 6 weeks and one year by a mean of 14.8mm ($p<0.01$). Moderate and minimal responders in terms of pain and function at one year after DIAM surgery, did not change over the first postoperative year of observation (Figure 10.6).

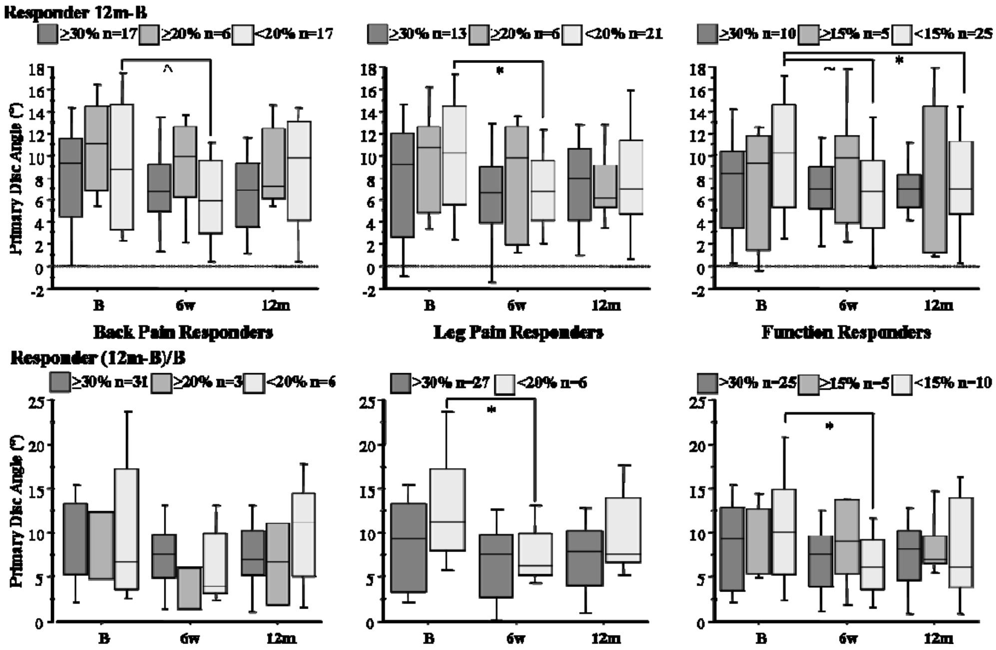


Figure 10.5: Serial change in primary disc angle (PDA) as derived from radiography within one year postoperatively according to back pain (left), leg pain (middle), and function (right) response, as reported by 40 patients after lumbar surgery augmented with DIAM. Group case numbers are indicated. Moderate (dark grey), minimal (medium grey), and non-responders (light grey) are included. Absolute response at one year (12m-B) is presented on the top row, normalised response at one year [(12m-B)/B] on the bottom row. Significant differences are shown: *p<0.05; ^p<0.01 ~p<0.001.

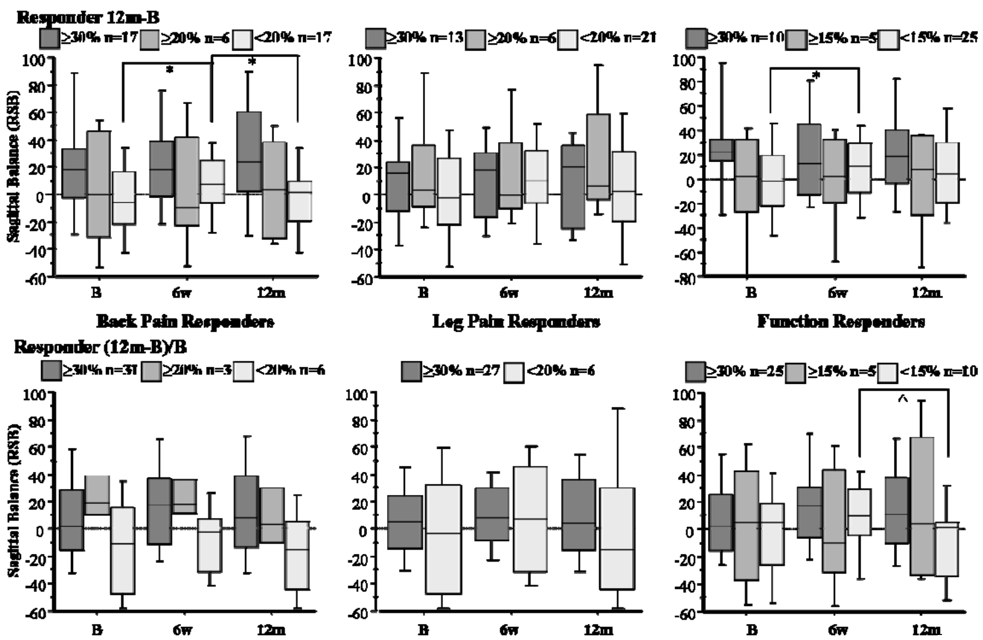


Figure 10.6: Serial change in regional sagittal balance (RSB) as derived from radiography within one year postoperatively according to back pain (left), leg pain (middle), and function (right) response, as reported by 40 patients at 12 months after lumbar surgery augmented with DIAM. Group case numbers are indicated. Moderate (dark grey), minimal (medium grey), and non-responders (light grey) are included. Absolute response at one year (12m-B) is presented on the top row, normalised response at one year [(12m-B)/B] on the bottom row. Significant differences are shown: *p<0.05; ^p<0.01.

10.3.3 Surface and skeletal spinal curvature

Baseline comparisons: When comparing surface curvature as determined via rasterstereography, with skeletal curvature as determined using plain lateral radiography, the only significant (weak) association found at baseline in the 33 cases with both sets of data, was between surface lumbar lordosis (Surface LL) and the radiographically-derived RoC1-6 [r=-0.35; p<0.05].

Early postoperative comparisons: Comparisons of change over the initial 6 week postoperative period in the same 33 cases showed a moderate association between thoracolumbar sagittal balance (GSB) as determined from the surface, and lumbar regional sagittal balance (RSB) as measured from radiography [r=0.50; p<0.01]. A weak relationship was shown between change in Surface LL and skeletally-derived lumbar lordosis (Skeletal LL) [r=0.36; p<0.05]. Significant surface versus skeletal curvature associations are presented in Figure 10.7.

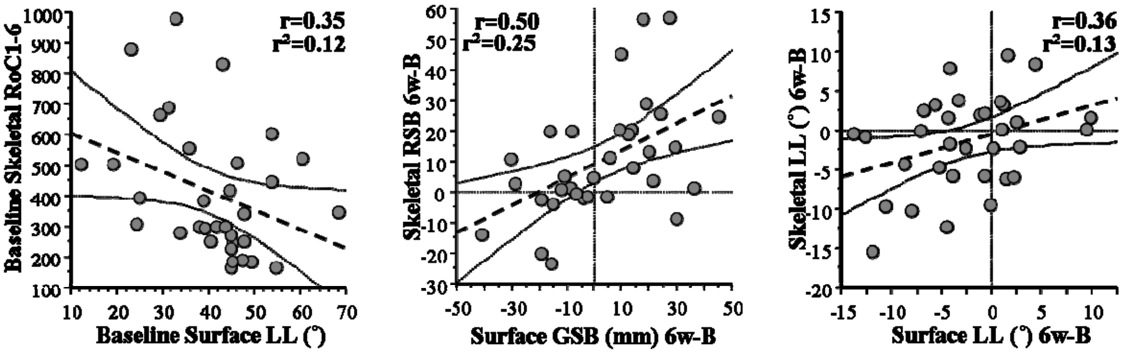


Figure 10.7: Statistically significant associations at preoperative baseline (left) and change at 6 weeks postoperatively (middle and right) between surface and skeletal curvature variables as measured via rasterstereography and radiography, respectively, in 33 cases for whom both were assessed. Trend-lines (dashed) and 95% confidence intervals around the mean (light curved lines) are indicated.

Comparisons of change in primary disc angle over the initial 6 week postoperative period and baseline lumbar sagittal balance as determined from radiographic imaging in 59 cases, split according to moderate, minimal and non-responder groups, has been illustrated in Figure 10.8. The strongest relationship between the two skeletal curvature variables was seen in non-responders, particularly in terms of absolute (r=0.62; p<0.001) and normalised (r=0.73; p<0.05) change in back pain.

10.4 Discussion

Results of this aspect of the investigation revealed interactions between HRQoL and surface curvature, HRQoL and the skeletal variables primary disc angle (PDA) and regional sagittal balance (RSB), as well as some comparisons between surface and skeletal curvature. Each will be discussed below in the context of available literature.

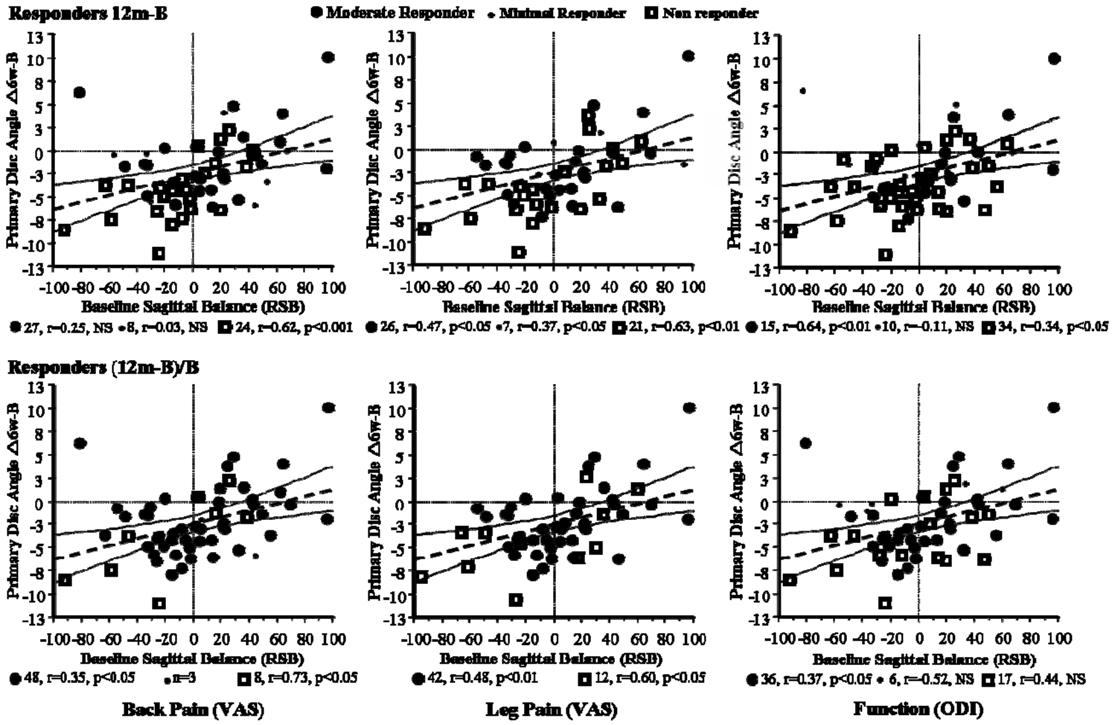


Figure 10.8: Associations between Baseline sagittal balance (RSB) and Primary disc angle change between 6 weeks and baseline (△6w-B) split by absolute responders [top; 12m-B] and normalised for baseline response [bottom; (12m-B)/B] for back pain (left), leg pain (centre) and function (right). Moderate, minimal and non-responders are indicated. Case number, r-value and level of significance are presented for each.

10.4.1 HRQoL versus surface curvature

No difference between responders and non-responders in terms of absolute or normalised back pain, leg pain or function, was noted for any of the baseline surface curvature variables examined in 39 cases via rasterstereography in this study. Additionally, no associations between pain or function and surface curvature were found preoperatively. Consequently, it may be surmised that features of a person's preoperative spinal posture, as determined from measurements based on the skin surface, are not clinical indications for lumbar decompression surgery augmented with DIAM. Although other investigators have not examined preoperative characteristics of ISP patients specifically, the results of the present series are in agreement with the majority of studies reported in Table 8.1 (9 of 12) that showed no difference between asymptomatic and back pain subjects in terms of surface-derived lumbar lordosis or sacral inclination. The two studies that revealed a difference had contrasting results; Adams et al (1999) reported a reduced LL associated with back pain, while Christie et al (1995) reported an increased LL in their LBP cases when compared to pain-free subjects. Direct comparisons between studies are difficult due to the heterogeneity between subject groups and varying methodologies; however it appears that association between posture and back pain is not predictable.

The lack of association between surface curvature and back-related pain and function, likely relates to the wide variability of adult posture seen in asymptomatic and symptomatic individuals (described earlier in Chapters 5 and 8, respectively). Another explanation is that altered body positioning as a result of degenerative disease affecting the segment, may be too small to exert forces on the spine that would result in an externally apparent postural reaction. This is not intended to diminish the possibility of a potential therapeutic effect (on symptoms) of a subtle change in alignment in a damaged segment. However, if change in posture secondary to pain were to occur, it might be expected that cases reporting high pain severity would represent those most likely to modify their posture in attempts to remedy symptoms; this was not shown for the 39 cases assessed with the methods used. The author also speculates that an individual experiencing sufficiently severe symptoms to appreciably change standing posture would require high levels of analgesia simply to maintain basic upright and ambulatory function. This scenario is arguably more likely in acute patients than those with chronic symptoms as assessed in this investigation. Similarly, undertaking rasterstereographic assessment in the present study required a degree of standing tolerance in patients, in addition to the demands of travelling to the appointment. The surgeon triaged patients for rasterstereography based on his perception of their ability to attend, and therefore cases with obvious postural dysfunction may not have been referred.

When surface derived LL and TK were examined according to change in normalised for baseline back pain response, both were shown to reduce (by 3.4˚ and 2.4˚, respectively) in moderate responders over the initial 6 week postoperative course. In contrast, non-responders had an increased LL (by 3.0˚; $p<0.05$) and only a slightly decreased TK (by 1.6˚; $p<0.05$). This result, which indicated an overall thoracolumbar flattening in cases showing the best improvement in back pain, modestly supports the surgeons' anecdotal observations that patients with less pain postoperatively are more comfortable and consequently stand straighter (Malone 2007b; Popovic 2007; Taylor 2010). Closer inspection of the data associated with the comparisons demonstrated in Figures 10.1 & 10.2, revealed that only 16 of the 30 cases identified as moderate normalised back pain responders had concurrent early flattening of their LL and TK. Consequently, the result of surface thoracolumbar flattening should be considered with caution. No other studies have reported on surface curvature after interspinous surgery in order to provide a suitable comparison for these results. Further investigation of surface spinal curvature after interspinous surgery may be warranted to elaborate the findings of the present investigation and to further test these surgeons' clinical impressions. However, additional cases may not necessarily substantiate the subtle changes detected, given the variability of adult standing posture and methodologic limitations (discussed in Chapters 5 and 8).

When assessing surface curvature in relation to patient-reported pain and function, this study showed that back pain tended to influence curvature variables (LL, LD, SB) rather than leg pain (Figures 10.1-3 and Table 10.4). Clinically, radicular leg pain presents secondary to nerve root compression via foraminal stenosis and commonly involves unilateral predominant symptoms that have the potential to alter ipsilateral weightbearing (Modic et al. 2005; Tarulli and Raynor 2007). Consequently, it might be argued that an individual's posture in the coronal plane is more likely to be altered with leg pain symptoms, than their sagittal plane posture. This could explain satisfactorily, the lack of discrimination that leg pain had for the surface curvature variables as assessed in the present study via rasterstereographic using sagittal profiles.

10.4.2 HRQoL versus skeletal curvature

This study revealed a difference at baseline in skeletal lumbar sagittal balance (RSB) between moderate and non-responder cases in terms of absolute (12m-B) improvement in back pain and function at 12 months. Back pain and function moderate responders (12m-B) had a positive RSB on average (13.0Rmm and 22.4Rmm, respectively) at their preoperative baseline. In contrast, non-responder's RSB was negative preoperatively (-8.7Rmm back and -5.3Rmm function; $p<0.05$). Further inspection of Table 10.4 shows that all responders (moderate and minimal) for both pain and function had a positive mean RSB preoperatively, while non-responders were negative. It is generally held that the range of normal sagittal balance, as determined from a C7 plumbline or sagittal vertical axis, is within 25mm of vertical, either negatively or positively (Jackson and McManus 1994). Given this criteria, and despite the RSB values for the present study not being reported in metric due to concerns with lateral x-ray distortion, all mean values for the 59 DIAM surgery cases examined at baseline appear to lie within this normal range. However, the notable difference detected between responder groups is an interesting result. In their study examining skeletal alignment after decompression and posterolateral spinal fusion for degenerative spondylolisthesis, Kawakami et al (2002) showed that cases with a preoperative RSB less than 35mm (as determined using the comparable LASD index employed in the present investigation), had superior improvement in pain postoperatively, than those with greater than 35mm RSB at baseline. Although their results appear to be in reasonable agreement (+10mm) with the normal range for sagittal balance described by Jackson and McManus (1994), Kawakami et al did not report actual values for their <35mm group, and therefore their results cannot strictly be compared with the present investigation.

The present results indicated a negative 'sway' posture (Smith et al. 2008) at baseline in cases whose back pain did not respond to surgical treatment with DIAM. Speculatively, a habitual sway standing posture may result in increased load on the passive posterior spinal structures, particularly in the low lumbar spine, and secondary to induced lumbar extension (Mitchell et al. 2008). This may be a result of inhibited supporting spinal musculature secondary to sustained stretch or elongation (O'Sullivan et al. 2002) and potentially also to maladaptive shortening of the (passive) posterior ligamentous complex (Cholewicki and McGill 1996). Speculatively, the imposed subtle segmental kyphosis in the presence of a DIAM may have encouraged an active compensation in local soft tissues that the ‘sway’ cases found difficult to tolerate. This concept would need to be verified in future investigation where postural classifications were a focus.

When the serial change in RSB in the first postoperative year is considered for the 40 cases, back pain non-responders changed significantly between each time-point ($p<0.05$), while responders remained similar across the year. Non-responders had a negative RSB preoperatively (-9Rmm), a positive RSB at 6 weeks postoperatively (9Rmm) and approximated zero RSB by one year after surgery. The wide variability in RSB in the cohort makes this result difficult to interpret. Given RSB was the only skeletal curvature variable that was associated (weakly) with patient symptoms (leg pain; $r=0.31$; $p<0.05$), it would seem that further exploration of skeletal alignment in terms of lumbar sagittal balance is warranted. The difficulty will be in controlling for influences on trunk inclination and the vertical axis like postural sway (Appendices VII.1) arm position (Appendix VII.2), the potential for multi-joint compensatory strategies (Appendix VII.3) and the verticality of the radiographic setup (Appendix IX). Assessment of postural sway in 11 healthy volunteers (standing in the clavicle position; Appendix VII.1) showed a mean (SD) AP excursion of 16mm (7mm) over a period of five minutes. Additionally, thoracolumbar sagittal balance was significantly different when volunteer’s arms were in each of three positions [by the side, clavicle and 90˚ elevation]; the higher the arm elevation, the more negative the GSB (Appendix VII.2). Further, the study described in Appendix IX revealed that true plumbline verticality of radiographic images should not be assumed. A system error of 1.25˚deviation from vertical was shown between the 14 radiography sites (16 buckeys) associated with imaging patients in the prospective phase of this thesis. Inserting a radio-opaque plumbline reference into each image setup, and concurrently using force-plate technology with imaging, may allow for a more precise measure of spinal alignment in lumbar surgery cases.

A significant difference in early change (by 6 weeks) in PDA between moderate and non-responders according to absolute (12m-B) back pain and function was shown; PDA in non-responders reduced by three times more than moderate responders. In terms of back pain, PDA reduced by 1.0˚ in moderate responders and by 3.9˚ in non-responders ($p<0.01$). In terms of function, PDA reduced by 1.2˚ in moderate responders and 3.5˚ in non-responders ($p<0.05$) (Table 10.6). Also, when normalised for baseline response in leg pain [(12m-B)/B] is considered, the 42 moderate responders had significantly less reduction in PDA than the 12 non-responders ($p<0.05$) (Figure 10.4). The serial results for PDA presented in Figure 10.5 also show significantly more reduction in PDA in non-responders, while change in moderate or minimal responders was not significant over the first postoperative year. Given the purported therapeutic effect of the DIAM is posterior distraction to induce a relative segmental kyphosis at the index segment in order to alleviate painful tissues (Taylor et al. 2007), these results concerning PDA are somewhat surprising. Technical guidelines for DIAM surgery outline that device-sizing should endeavour to provide posterior distraction to the maximum tension of the supraspinous ligament, to the limit of parallel end-plates and before actual kyphosis at the segment (Medtronic 2006). Close inspection of the data for PDA (not shown) at the 6 week time-point showed that there were three cases whose index segment went into actual kyphosis, two (of 24) were non-responders (PDA -0.07˚ and -1.3˚) and one (of 27), with the largest kyphosis, was a moderate responder (PDA -2.0˚). Considering the response results of the 59 cases assessed, it appears reasonable to conclude that cases whose disc angle at the primary index level flattens into relative kyphosis the most, will not respond in terms of back pain and function at one year after surgery augmented with DIAM. The postulated therapeutic biomechanical effect of lumbar surgery using DIAM might therefore be questioned. This is discussed further in Chapter 11.

Assessing spinal curvature in static standing, either from the skin surface or vertebra as has been employed in this thesis investigation, may not have been the most suitable posture for establishing predictive determinants of success with DIAM-augmented, or other lumbar surgeries. Although it is reasonable to investigate a posture involving lumbar extension (e.g. standing) in a cohort of patients for whom an extension-buffering (Richards et al. 2005; Wilke et al. 2008) surgical implant has been clinically reasoned to suit, the wide variation of adult standing may have limited the capacity to detect subtle postural differences that were associated with symptoms. It is unlikely that all patients followed in this study had pain provoked by the same postures and mobility. Instead, it is probable that sub-groups of postural and movement impairments (O'Sullivan 2005; O'Sullivan et al. 2006) existed within their number. However, differences between them may not be discreet enough to allow for further subgroup analysis. Assessing spinal curvature in subjects with pain and dysfunction would be best achieved by exploring functionally-relevant postures that align with patient-reported symptoms. Speculatively, cases who describe provocation in sitting (lumbar flexion) have a potentially ‘different’ spinal curvature from those reporting pain in standing (lumbar extension). By way of example, in their study comparing industrial workers with or without flexion-related back pain, O’Sullivan et al (2006) showed that the cases with back pain, habitually sat closer to their lumbar flexion end-point. Consequently, an exploration of the flexed sitting posture was more likely to test the outer elastic range of the symptomatic lumbar region (or segment) where stresses on the passive posterior elements were potentially increased (Scannell and McGill 2003) and nociceptive sensitisation more likely.

Further, Mannion et al (2005) showed that change in the range of lumbar flexion (determined from the skin surface in standing forward flexion) after decompression surgery for disc herniation, was strongly associated ($r=-0.82$; $p<0.0001$) with change in patient-reported function (Roland-Morris Disability Questionnaire). Yet, although they reported a significant flattening to LL in standing postoperatively, it was not associated to disability. The effect on lumbar mobility is not well documented for ISP surgeries, and is predominantly based on cadaveric studies (Swanson et al. 2003; Richards et al. 2005; Wilke et al. 2008). Assessment of the influence of ISP devices on lumbar mobilty in vivo, particularly in the sagittal plane, may represent a useful addition to the literature. Employing skin-surface measurement instruments to assess thoracolumbar posture may represent a safe and effective means of monitoring ISP cases postoperatively. This may be of most benefit in the early postoperative period when change has been shown to occur, but also subsequently to identify whether a critical time-point for reversion back to baseline exists.

It is intuitively satisfying to note the early postoperative changes to surface thoracic kyphosis and lumbar lordosis, and skeletal lumbar sagittal balance and segmental disc angle, following insertion of a DIAM interspinous device. The latter trend confirmed the primary hypothesis (#4) that a small segmental kyphosis would occur at the index segment. Speculatively, subsequent adaptation in soft-tissues over time, coincident with putative changes in vertebral alignment, resulted in a progressive accommodation to the DIAM-augmented surgery. The clinical behaviour of back and leg pain, which is the critical test for surgical outcomes (Mannion et al. 2007), was not strongly associated with these changes in spinal curvature.

<u>10.4.3 Surface versus skeletal curvature</u>

The expectation for only weak associations between surface and skeletal spinal curvature variables was generally confirmed and is in agreement with the literature and collateral studies presented in Appendices VIII.1-3. Only one significant baseline association ($r=0.35$; $p<0.05$) in the present study was shown between surface-derived lumbar lordosis and skeletally-derived radius of curvature (from L1-S1). While change at 6 weeks in surface and skeletal lumbar lordosis was also weakly associated ($r=0.36$; $p<0.05$). In addition to lumbar lordosis (or related measures), this thesis investigation also explored potential relationships between other spinal curvature variables, however no other associations were noted. The lack of similarity between surface and skeletally derived spinal curvature were explored in additional studies, putatively relating the differences to vertebral morphology (Appendix VIII.2) and variable thickness of overlying skin tissues (Appendix VIII.3). Inspection of the scatter-plots in Figure 10.7 indicates generally weak correlations with the majority of data points outside the 95% confidence interval with little variance accounted for by the comparators.

Surface and skeletal lumbar lordosis comparisons have established both a poor ($r=0.30$) (Bryan et al. 1989) and high (r=0.80) (Willner 1981) correlation when flexirule and pantograph surface measures were compared, respectively, with skeletal measures derived from radiographs. Discrepancies suggest an inconclusive relationship between surface and skeletal lumbar contours, with predictive models based on the assumption that distances between the skin profile and the skeletal spinal curve are different and vary with spinal level and posture (Willner 1981; Bryant et al. 1989; Sicard and Gagnon 1993). Comparisons reported in the literature are limited to describing the relationship of lumbar lordosis alone. The study presented in Appendix VIII.1 showed a fair correlation for both lumbar lordosis and sagittal balance (r=0.38, 0.32, respectively; p<0.01) between simultaneously-imaged surface and skeletal curvature in 69 women. The morphometric assessment of lumbar vertebrae detailed in Appendix VIII.2 indicated the potential bony contribution to the difference between surface and skeletal curvature in the lumbar region. Vertebral body waists were shown to increase from L1 to L5, while total vertebral body length peaked at L3 and was smallest at L5. Perhaps most notable is the increasing AP thickness of subcutaneous tissues overlying low lumbar spinous processes, as compared to the low thoracic and upper lumber levels (Appendix VIII.3). More formal investigation of these associations appears warranted, particularly with respect to identifying suitable methods for monitoring serial change in spinal curvature, without the need for ionising radiation. Examining tissue thickness of the thoracolumbar and lumbosacral fascial tissues may contribute to an improved understanding of soft tissue recovery after decompression and ISP-related surgeries.

Vertebral morphology was shown to be highly predictive of Cobb-derived thoracic curvature, a relationship that improves when a localised mid-region curve involving the kyphotic apex is assessed compared to the entire thoracic spine (Goh et al. 1999c). In contrast, poor association is noted between disc morphology and thoracic curvature (Goh et al. 1999c). Given the lumbar spine comprises more disc height than in the thoracic region (Bernhardt and Bridwell 1989; Gelb et al. 1995), this may be another explanation for the weak association between surface and skeletal curvatures.

A moderate association (r=0.50; p<0.01) was shown for early change (6 weeks) in thoracolumbar sagittal balance as derived from rasterstereography, and regional lumbar sagittal balance as determined from radiographs. Although there was no association between GSB and RSB at baseline, their related change in the early postoperative period indicates similar spinal compensations with reference to the sagittal vertical axis. The scatter-plots presented in Figure 10.8 showed stronger associations in non-responders than responders, between early change in primary disc angle and baseline sagittal balance, as determined from radiographs. The strength of any correlation between surface and skeletal curvature may therefore depend on pain or disability in patients.

10.5 Conclusions

Spinal posture measured from the skin surface is not a prognostic determinant for patient-reported improvement after lumbar surgery augmented with DIAM. A negative lumbar sagittal balance as determined from radiographs is a preoperative indicator of non-response, while a positive RSB suggests at least minimally significant improvement in back pain and function. Concurrent mean flattening of thoracic kyphosis and lumbar lordosis (surface) in the first 6 weeks postoperatively occurred in moderate back pain responders suggesting initial spinal straightening related to improved back comfort. On average, non-responder's RSB became more positive a 6 weeks postoperatively and then resumed baseline values at one year; responders remained the same. Primary disc angle as determined skeletally from radiographs reduced more in non-responders than in responders.

CHAPTER 11

Discussion

11.1 Introduction

The primary aim of this investigation was to test the hypothesis that patient-reported pain and function would show clinically significant improvement along a two year postoperative course (compared to preoperative levels) after DIAM-augmented lumbar surgery. The study also examined the putative biomechanical effect of interspinous distraction on spinal curvature, with a hypothesised expectation that relative skeletal segmental kyphosis would be induced at the index level. Additionally, spinal curvature, as determined from the skin surface, was not expected to alter postoperatively, despite the anticipated improvement to patient comfort. The combined result of these study objectives was to contribute to improving clinical guidelines for the use of ISP augmentation (DIAM) in the surgical treatment of lumbar spine disease.

Clinical outcomes comprising patient-reported health related quality of life (HRQoL), and spinal curvature as determined from the surface via rasterstereography, and skeletally from plain erect lateral radiographs, were collected for 81 cases over their two year postoperative course. Patient-reported HRQoL assessment centred on the primary outcomes of change in back pain, leg pain and function, using validated outcome instruments according to expert recommendations. The HRQoL questionnaire was administered at seven time-points over the two year period of observation, with subsequent analyses involving comparisons between category sub-groups and responders. Secondary HRQoL outcomes included patient satisfaction with symptoms and pain medication use in relation to their preoperative levels. Additionally, incidence data were examined to determine the rate of subsequent surgeries.

Assessment of surface curvature using rasterstereography involved serial testing of features of thoracolumbar spinal alignment and angulation in 39 cases. Subjects were examined over their two year postoperative course, with emphasis given to the results of 27 cases from data for four time-points during their first postoperative year. Skeletal lumbar curvature was assessed in 59 cases between baseline and six weeks postoperatively, and in 40 cases with serial data out to one year after surgery. The three sets of clinical outcome data were examined for interactions in order to identify relationships between the subjective patient-reported outcomes, and the objective measurements of surface or skeletal spinal curvature. This was executed in relation to subject response to their surgery.

The summarised key findings of the investigation were:

1. Improvement in patient reported back pain, leg pain and function to a minimal clinically significant level was sustained to two years after DIAM-augmented surgery, with the critical time-point for postoperative improvement being three months.
2. Primary facet cases did not have superior response to surgery in terms of pain and function than cases with primary disc disease.
3. When change in patient-reported pain and function was considered according to sub-group analysis, major predictors of a significant lasting (to 2 years) response to surgery were: foraminal stenosis, single segment surgery, and employing more than one adjunctive decompression procedure. Secondary factors influencing recovery were: male gender, L4/5 or L5/S1 index segment disease, and preoperative leg pain that was worse than back pain.
4. Depth of the surface lumbar curvature and skeletal disc angulation at the index segment both reduced in the initial (6 weeks) postoperative period. However, no change to surface thoracolumbar spinal curvature or skeletal lumbar curvature compared to preoperative baseline occurred from 3 months after surgery out to two years.
5. Features of thoracolumbar spinal curvature, as determined from the skin surface, were not prognostic determinants of postoperative response to the surgery. However, cases showing important clinical improvements in back pain at 12 months after surgery compared to baseline values, showed straightening of their thoracic and lumbar surface curvature at 6 weeks postoperatively.
6. Having a negative lumbar skeletal sagittal balance preoperatively was more likely to result in a poor postoperative response than cases with a positive RSB. Primary disc angle (skeletal) reduced more at 6 weeks postoperatively in non-responders than responders.

Several additional findings and themes specific to each of the results chapters (Chapters 4, 5, 6, 7, 8, 9, and 10) have already been discussed. Consequently, this main discussion focuses on the key predictive outcomes summarised above, and in particular, as they pertain to an improved understanding of the clinical indications for lumbar surgery involving the Device for Intervertebral Assisted Motion, and ISPs in general. Discussion will be in the context of the presented literature review and is organised to present three main themes: implications of the primary outcomes for the study; clinical indications for DIAM-augmented lumbar surgery; and considerations of response relating to the surgical technique. Limitations of the investigation will be discussed as they relate to each of these themes, within the relevant section.

Table 11.1 summarises the findings of the investigation in terms of the main characteristics for a favourable response in back pain, leg pain or function after DIAM surgery. These characteristics are discussed further.

Table 11.1: The main characteristics of responders (and non-responders) to DIAM-augmented lumbar surgery. Significant findings are indicated in bold ($p<0.05$), with noted trends also listed.

	Responder	Non-responder
Demographic	**Foraminal Stenosis**	Degenerative Spondylolisthesis
	Male	
	Primary disc pathology	
Preoperative Status	Predominant leg pain	
	Positive skeletal sagittal balance	**Negative skeletal sagittal balance**
Surgery	**Multiple decompression procedures**	
	Single segment	
	L4/5 or L5/S1 index level	
Early Postoperative period	Thoracolumbar postural straightening	
	Less flattening of the PDA	**More flattening of the PDA**

PDA=primary disc angle

11.2 Implications of the primary outcomes of the study

This theme of the discussion focuses on the primary outcomes for the study including: pain and function in terms of MID recommendations and the effectiveness of DIAM-augmented lumbar surgery; change in spinal curvature in relation to the purported biomechanical effect of ISP devices; and the relationships between pain and function and spinal curvature as predictors of improvement.

11.2.1 Effectiveness of DIAM-augmented lumbar surgery: patient-reported pain and function

The present study showed that the 81 prospective cohort cases had improved back pain, leg pain, and function two years after their surgery involving the DIAM, to the minimum level representative of a clinically appreciable difference (Pain >20%; Function >15%). Best reduction in pain (back and leg) and function was achieved by the 6 week and 3 month postoperative time-points, respectively. However, no outcome had improved by two years postoperatively to levels considered either clinically important (≥30%) when serial change compared to baseline was considered in conjunction with the definitions for MID proposed by Dworkin et al (2008) and Ostelo et al (2008). Additionally, less than half the cohort was satisfied with their level of pain and/or disability at two years after their surgery. It might also be argued that a surgical failure rate of 13 of 81 cases in the prospective cohort as defined by reoperation at the initial index segment, although better than that reported for the retrospective cohort (11 of 39; Table 2.3), represents an unacceptable reoperation rate (Hu et al. 1997; Deyo et al. 2004). Additionally, the decrease in the number of responders between 12 and 24 months, is indicative of unsustained initial improvement, which might not be considered sufficiently long term given the natural history of lumbar degenerative disorders (Roland and Morris 1983;

Amundsen et al. 2000; Baldwin 2002; Gibson and Waddell 2007b; Vernon-Roberts et al. 2008).

Therefore, the group outcomes for pain and function described in this thesis investigation indicate an inferior response to surgery than might be considered acceptable to provide endorsement for employing DIAM-augmented decompression surgery, in the treatment of low back pain and related lumbar pathologies. However, this conclusion has been based on the results of a heterogeneous cohort of 81 cases who underwent surgery combining decompression and the DIAM, within which certain sub-sets of subjects showed superior improvement. Adequately powered future studies designed to investigate a more homogeneous cohort of patients, may reveal a better response than reported for the cohort described in this thesis investigation. Of additional consideration relating to the 81 cases presented in the prospective series, is that they were a group of patients with chronic symptoms that were present for longer than 12 weeks, and for whom other non-surgical treatments had not resulted in appreciable improvement. As such, the proportion of responders described might be considered an improvement for the group at large.

The patient-reported outcomes reported in this thesis should be interpreted cautiously in relation to the study limitations. Subject response according to clinical indications is elaborated later.

11.2.2 Effectiveness of DIAM-augmented lumbar surgery: spinal curvature

Biomechanical studies reported for the DIAM and other ISP implants provide ex vivo evidence for an induced posterior element distraction (Richards et al. 2005) by showing reduced posterior disc anular pressure (Swanson et al. 2003; Wilke et al. 2008), facet joint unloading (Minns and Walsh 1997; Wiseman et al. 2005), and buffered lumbar extension (Minns and Walsh 1997; Lindsey et al. 2003; Richards et al. 2005; Phillips et al. 2006; Wilke et al. 2008), in the presence of an ISP device. Studies performed in vivo using upright MRI in patients implanted with the X-Stop, also showed increased central canal and intervertebral foraminal area through reduction of disc anulus and ligamentum flavum infolding (Siddiqui et al. 2005; Siddiqui et al. 2006a,b). Consequently, the early postoperative reduction in index disc angle seen skeletally in the present study was anticipated, despite previous investigators reporting no significant change to disc angle in vivo, at one year after ISP surgery (Anderson et al. 2006; Siddiqui et al. 2006b; Kim et al. 2007).

Surface lumbar flattening and relative skeletal segmental kyphosis at the index level, only occurred in the short term in cases assessed in the present study. In terms of skeletal curvature, this was in agreement with Sobottke et al (2009), who showed reduced intervertebral angle in the early postoperative period after ISP (including the DIAM) surgery, with a subsequent loss of this purported therapeutic ‘correction’ by 12 months postoperatively. The hypothesised effect of a skeletal relative segmental kyphosis imposed on the index segment after DIAM-augmented surgery is therefore supported by the present investigation. However, this biomechanical effect was shown to reduce between the six week and 12 month postoperative period, despite a relatively sustained improvement in pain and function during that time. The author has speculated that the diminished effect is due to subsequent adaptation in soft-tissues, potential for device settling, and coincident changes in vertebral alignment, while the clinical behaviour of back and leg pain and back-related function does not appear to be a strong influence on spinal curvature. Whether a flattened lumbar curvature in the early postoperative period relates solely to the DIAM, or alternatively from the adjunctive decompression procedure(s), is not appreciated from the present investigation. The results described by Mannion et al (2005) that showed flattening of the surface lumbar lordosis two months after decompression surgery (without ISP), suggests that patients' soft-tissue recovery from the surgical approach itself, may best explain the early reduction in surface lumbar depth seen in the present series. The sequelae of postoperative tissue recovery would be expected to diminish over time, and therefore may explain the reversion of the skin contour back to baseline values. Given the weak relationship between surface and skeletal lumbar lordosis shown in the present investigation, it is unreasonable to directly implicate postoperative soft tissue recovery as the explanation for the observed flattened primary disc angle, which seems most attributed to the influence of the DIAM. However, an interesting finding of the Wilke et al (2008) cadaveric study that assessed the mechanical effect of four ISP devices, including the DIAM, was that a small (0.5-0.7°) kyphotic tilt at the index segment occurred after the 'defect' procedure, which involved a bilateral hemifacetectomy and resection of the flaval ligaments, <u>before</u> any ISP was implanted. Speculatively, this finding suggests that the passive 'stability' of the segment was influenced by removal of posterior osseoligamentous tissue, which altered the segmental mechanics. It appears reasonable that the instantaneous axis of rotation (IAR) of the segment migrated anteriorly toward the remaining intact structures (Haher et al. 1992), thereby producing an anterior rotation of the cephalad vertebra (Rousseau et al. 2006).

The noted reversion back to baseline segmental angulation and thoracolumbar posture and alignment may be indicative of the posterior stabilising structures 'recovering' from the surgical approach and introduced device. If the initial segmental response to the surgery was anterior rotation of the cephalad vertebra (producing kyphosis), promoted as a consequence of approach-related tissue injury (and anterior IAR), then a period of recovery would be expected before the posterior ligamentous complex and lumbosacral myofascia regained their preoperative extension moment at the segment. Recovery might then restore the posterior myofascial tissue integrity in order to impose a more typical posterior rotation at the cephalad vertebra and a subsequent posterior migration of the IAR toward the implant. This mechanical concept would require verification from studies involving in vivo flexion-extension imaging or finite element modelling where the erector spinae and associated active structures would be accounted for.

As briefly discussed in Chapter 10, interesting interactions between pain and function and spinal curvature postoperatively were shown in the present study. Responders had positive skeletally-determined lumbar sagittal balance preoperatively, early (6 weeks) straightening of their thoracic and lumbar curvatures (as determined from the skin surface), and less average early flattening of the skeletal primary disc angle, as compared to non-responders.

It is perhaps reasonable to expect this surgeon's patients to stand straighter after surgery, given the routine postoperative rehabilitation protocol and associated functional advice dictated they resume their typical upright postures and normal activities as soon as possible. A patient's motivation to maximise the therapeutic potential of the surgery may arguably be at its strongest immediately postoperatively, with a more conscious effort therefore directed toward maintaining a suitable upright posture. Although the postoperative rehabilitation protocol was treated as a constant for the cases assessed in the prospective series, assessing for each patient's compliance to the rehabilitation programme may have clarified whether the postural changes related to exercise. However, exercise compliance was not considered a core postoperative variable in this thesis study, but its potential influence on surface spinal curvature and pain and function is acknowledged. In a recent study investigating a cohort of microdiscectomy cases from the same neurosurgical practise employed for this DIAM investigation, Lynn (2009) reported superior improvement in back pain at 12 months in cases who commenced an early postoperative exercise protocol, compared to those who did not. It seems reasonable that the recovery of soft tissues, in particular myofascial and ligamentous structures after DIAM-augmented surgery, warrants further investigation.

The result that responders were cases with the smallest change to disc angle compared to non-responders was surprising. Surgical guidance for using the DIAM is to implant the largest device possible, which is practically defined by tensioning the supraspinous ligament to its pre-failure limit, yet stopping short of imposing an actual kyphosis at the segment (Taylor 2001; Medtronic 2006; Taylor et al. 2007; Palmer 2009; Taylor 2009). This implies that the surgical aim in implanting a DIAM (or other ISP implant) is to distract the posterior elements as far as anatomically safe, suggesting the largest change in disc angulation possible, the better. The results of the present study do not support this contention, which perhaps then questions the therapeutic biomechanical effect of the device in vivo. The size of the implant used, determined with an intraoperative sizing procedure based on anatomical constraints, appears less relevant than simply imposing a small relative flattening to the disc angle. The therapeutic effect of the ISP device may instead relate to a subtle change to stresses at the segment subsequent to an altered IAR, rather than a measurable alteration in sagittal alignment. The potential influence of a stress-shielding type phenomenon, analogous to Davis's (soft tissue adaptation) or Wolff's (osseous tissue adaptation) Laws (Stedman 2006), may warrant further exploration in attempts to better explain the effect of the DIAM (or other ISPs) in vivo. Rather than the emphasis of the mechanical effect being on a change in segmental angulation secondary to posterior element distraction, it may instead be predominated by a posterior relocation of the axis of rotation for the segment toward the ISP implant. The resultant subtle change to segmental angulation may initiate an adaptive response in the tissues local to the device as compensation to the altered influence on translational or rotational moments around the IAR (Yoshioka et al. 1990; Haher et al. 1992; Rousseau et al. 2006).

Another consideration in relation to a surgeon's conscious and potentially intended control of the disc angulation imposed on the index segment during device implantation, is the fact that ISPs are inserted when the patient is in a weight-supported, prone, and slightly flexed spinal position, devoid of active myofascial influence secondary to the anaesthesia. Consequently, end-plate angulation achieved perioperatively may have little relationship to what the end-plates assume with axial loading and the influence of active muscles. It is therefore difficult to provide further guidance to surgeons as to what constitutes the most effective perioperative change in angulation. Further study comparing segmental angulation achieved perioperatively, and at immediate and sequential postoperative stages, may explain this further. Realistically, the extent to which any probable subtle change (if any) is measurable from suitable imaging is questionable given potential methodological error.

11.2.3 Limitations potentially influencing the primary outcomes

There are a number of limitations within the current thesis that require acknowledgment. Studies of an observational nature (like the present thesis) are exposed to bias, the effect of confounding, and inappropriate statistical analyses (Hanson and Kopjar 2005; Petrie 2006). Placebo effects have also been shown in studies involving surgical implants (Deyo et al. 2004). Aspects of these, as they relate to this investigation, are discussed below.

Bias: This study followed cases for which the surgical intervention with DIAM was non-randomized and based on the clinical decision making of one neurosurgeon. Similarly, patient categorisation for the study was influenced by the surgeon's: assessment of the patient, their pre-surgical work-up, interpretation of available imaging and clinical experience. In part, the author's postoperative case-note audit provided face validity to the subject-categorisation procedure. The single centre subject source allowed control for the group in terms of their surgery and the clinical rationale underpinning the decision to use the DIAM. All consecutive patients with surgery scheduled within a set time-frame were intended for the study based on determined inclusion criteria. However, several patients were excluded during the surgeon's preoperative triage, despite progressing on to DIAM surgery (Figure 3.1). Most case omissions were explained via exclusion criteria however not all occasions were reasoned. Several cases (n=8) did not consent to study inclusion at the cohort formation stage, which may indicate selective nonparticipation of certain types of patients; the reverse may also be true for those who did agree to participate (Black 1996; Landewe and van der Heijde 2007). A degree of 'completers' bias may have existed wherein those perceiving effective treatment remained in the study and therefore provided more favourable results than might have been actually true (Landewe and van der Heijde 2007). In order to balance this effect in statistical analysis, the LVCF imputation method was employed and carried forward the generally 'poor' last time-point measure of cases with increasing symptoms that progressed to additional surgery.

The LVCF method assumes an unchanged condition over time and is considered a conservative approach in studies evaluating treatments aimed at improving clinical symptoms (Twisk and deVente 2002; Shao and Zhong 2003; Landewe and van der Heijde 2007). However, if the natural course of the measured variable is progressive worsening, as might be said for degenerative spinal conditions, then potential for spurious results exists (Landewe and van der Heijde 2007). Consequently, the LVCF method was employed only for the HRQoL outcome assessment where the hypothesised effect of DIAM-augmented surgery was for improvement compared to baseline. It might also be rationalised that the natural history of lumbar spinal stenosis dictates that 70% of patients stay the same over the long term (Johnsson et al. 1992) and therefore the greater majority would be unchanged without the surgical intervention. Given approximately 50% cases in the present study had a clinically significant response to the intervention by two years, improvers in the current cohort were more numerous than would be expected according to the natural course of the disease (15%; Johnsson 1992).

It may be argued that the two year assessment for this thesis represents a short period of observation, particularly given the apparent deterioration (although not statistically significant) from the time of peak improvement at 3 months. Other studies have reported that early (2 to 6 months) outcomes after decompression surgery are generally maintained (Amundsen et al. 2000; Hakkinen et al. 2003; Weinstein et al. 2008a). Clinically significant deterioration of symptoms beyond four years after decompression surgery is reported to be unlikely (Amundsen et al. 2000). Extending the follow-up of the present series to four postoperative years may better determine any significance of the deterioration in pain and function.

Confounders: Confounding is a major source of bias in observational studies (Hanson and Kopjar 2005; Petrie 2006; Hayden et al. 2009) making it difficult to relate observations to a single intervention or influence. Although this thesis assessed the effectiveness of lumbar decompressive surgery augmented with DIAM in a quasi-experimental way, the lack of a comparison group, particularly decompression alone surgery, meant that observed effects could not be confidently apportioned to the DIAM itself. It was therefore difficult to discriminate the effect of the primary surgery from the role of the DIAM. This limitation was highlighted in the result for the prospective cohort where cases receiving more than one adjunctive decompression procedure in addition to their DIAM, had more relief of their leg pain than cases operated with a single decompression. The study reported in Appendix X, comparing the results of 29 primary disc cases in the prospective cohort with 48 microdiscectomy-alone patients from the same surgeon, showed superior improvement in leg pain ($p<0.001$), function ($p<0.01$) and back pain ($p<0.05$) in the microdiscectomy-alone patients, at one year after surgery. Despite the limitations of the study, this result highlights the need to compare surgery using the DIAM to its more traditional decompression alternatives. Interestingly, Richter et al (2010) have recently questioned the role of the Coflex ISP device as an augmentation to decompression surgery for LSS, having not shown superior outcomes in their Coflex plus decompression group. The need for ISP-based comparison studies is elaborated in Chapter 12.

Subjective outcomes based separately on surgeon and patient opinions have been shown to agree only in 50% of cases (Lattig et al. 2009). In addition, patient-reported outcomes like pain and functional status attract more bias than the incidence of revision surgery or postoperative complications (Hanson and Kopjar 2005). Psychological attributes (Turner et al. 2000; Mannion et al. 2001) and preoperative expectations (Mannion et al. 2009) are known influences on patient perception of disability and outcome; however these potential confounders were not specifically assessed in the present investigation where pain and function change scores were the primary focus. Other confounders that were not specifically assessed, may have influenced the surgical outcome and patient-reported pain and function over the course of the two year time period. These could have included whether patients: were involved in a compensation claim, had a high BMI, or other comorbidities, and/or received postoperative interventions for pain (like manual therapy or facet joint injections) that were not documented in the surgeon’s case notes. Apart from the initial surgeon-declared comorbidities and those that patients recorded on their time-point questionnaires, not all potential confounders were strictly monitored given the wide range of variables already being assessed in subset analyses.

While the case retention for this thesis investigation was generally very good for the two year period of observation, the baseline cohort essentially differed from that reported at two years after surgery. By way of explanation, the cross sectional analyses performed using baseline values for preoperative prognostic determination, best reflected the actual status of the cohort, as compared to subsequent time-points where fewer measured data were available due to attrition. At baseline, subjects collectively had elected to receive the same treatment (broadly, back surgery) and might therefore be considered of prognostic similarity. However, baseline likeness probably decreased over time owing to further interventions, changeable comorbidities, adverse events and shifting compliance. The increased variation in patient-reported pain and function, seen for the one and two year postoperative time-points in the present series, supports this notion.

The subjects enrolled for both the retrospective and prospective phases of the thesis had varied diagnoses, but particularly differed with respect to their preoperative levels of pain and function. As discussed in Chapter 10, diverse baseline values make comparisons to MID recommendations difficult. The absolute and normalised (for baseline) methods employed in the present study tend to bias the high and low pain (or function) patients, respectively. However, consecutive patients from a single neurosurgeon reflect a clinical reality presenting for surgical intervention for lumbar pathology, and therefore all cases should be represented in clinical trials. A randomised, case-control, longitudinal observational study comparing decompression alone with decompression plus DIAM, may mitigate this issue. An investigation comparing decompression plus DIAM or DIAM in isolation may represent a further improvement, but based on this thesis where only two DIAM alone cases occurred within a recruitment period of one year, achieving adequate comparative samples may be preclusive.

Assessing sagittal lumbar motion using end-point flexion and extension images, may have been a valuable additional outcome variable, particularly given the DIAM is purportedly a motion-preserving surgical intervention (Kim et al. 2007; Taylor et al. 2007; Guizzardi and Petrini 2008). However, radiographic assessments in this investigation were intentionally aimed to conform to the routine practise of the surgeon in order to limit participant burden; consequently, only erect plain lateral radiographs were available. Assessment of dynamic skeletal lumbar curvature after surgery using DIAM may add valuable information regarding the biomechanical effect of the device. Rasterstereography does not have the capability to assess lumbar motion given the static nature of its assessment and requirement for gridline projection on the skin surface. The safety advantage of measuring spinal curvature using surface-based instruments is attractive when compared with serial radiographic imaging. Upright MRI, or other surface curvature devices that have the capacity for measurements in functional postures, may be a useful alternative.

11.3 Clinical indications for lumbar surgery involving the DIAM

This aspect of the chapter will discuss the clinical indications for lumbar surgery employing the DIAM, with emphasis placed on response to surgery for the diagnoses represented in this investigation: lumbar spinal stenosis (foraminal and central canal); disc degeneration; facet joint pain syndrome; and degenerative spondylolisthesis. Additional demography-based prognostic determinants revealed in the study are also discussed.

No known previous studies have identified predictors of success for surgery using the DIAM, either in relation to the indication for surgery or to other demographic baseline factors (such as age, gender, anatomical or diagnostic involvement, preoperative pain and function levels, etc.). Consequently, the literature tends to suggest indications based on developer or marketed recommendations and retrospectively audited case series (Medtronic 2006; Taylor et al. 2007) (Table 4.1). The present study aimed to identify prognostic determinants of successful DIAM-augmented surgery, which could be identified preoperatively and may assist in guiding clinical pathways for patients.

Investigations examining outcome predictors for decompression surgery, generally in treatment of lumbar spinal stenosis, have also had mixed results with this endeavour. An attempted meta-analysis could not identify predictors based on limited studies (Katz et al. 1991; Katz et al. 1996), while a later meta-analysis concluded that patients with multiple symptoms had a poorer result, irrespective of the decompressive method used (Niggemeyer et al. 1997). There is reportedly more accuracy in predicting unsuccessful, rather than successful outcomes (Spratt et al. 2004), such that an algorithmic model for triaging patients preoperatively is promoted. A recent systematic review (of 21 studies) showed that coexisting depression and preoperative walking ability were independent predictors of poorer subjective postoperative outcome (Aalto et al. 2006). Three studies have shown that patients with preoperative back pain that is worse than their leg pain respond less favourably to lumbar decompression for LSS (Atlas et al. 2000; Yamashita et al. 2006; Kleinstuck et al. 2009).

11.3.1 Lumbar spinal stenosis

The greatest support in the literature for the use of ISP technologies is in the treatment of lumbar spinal stenosis. Investigations examining X-Stop surgeries in particular have provided the primary evidence for their use (Hannibal et al. 2006; Kondrashov et al. 2006; Brussee et al. 2008; Zucherman et al. 2008; Kuchta et al. 2009; Sobottke et al. 2009). Decompression surgery is a generally accepted progression for successfully treating older patients (>65 years) with LSS who have failed conservative management and continue to seek medical intervention (Niggemeyer et al. 1997; Atlas et al. 2000; Gibson and Waddell 2005; Yamashita et al. 2006; Malmivaara et al. 2007; Weinstein et al. 2008c; Chou et al. 2009a). With an aging population, rates of decompressive surgery are expected to increase in developed countries (Ciol et al. 1996a; Melloh et al. 2008; Deyo et al. 2010), which may motivate the continued development and progression of less invasive spinal surgical technologies (Jaikumar et al. 2002; Chiu 2004; Gibson and Waddell 2007b; Armin et al. 2008; Harrington and French 2008; Kanter and Mummaneni 2008; Oppenheimer et al. 2009).

In lumbar spinal stenosis (LSS), diameters of the central spinal canal, lateral recess or intervertebral foramen may be narrowed or have an abnormal shape secondary to developmental or degenerative processes, or a combination of both (Kirkaldy-Willis et al. 1974). Neural tissue compression results from either bony or soft tissue encroachment into the neural space, centrally (CS), or laterally (FS) (Yong-Hing and Kirkaldy-Willis 1983; Arbit and Pannullo 2001). Lumbar extension motion surpass axial loading as the predominant influence on reducing the cross-sectional area of the dural sac (Yang and King 1984; Chung et al. 2000), and therefore employing an extension-buffering interspinous device (Wiseman et al. 2005; Phillips et al. 2006; Wilke et al. 2008) appears a promising biomechanical resolution for the problem.

LSS is a common clinical condition, particularly in those over 65 years, with all stenotic cases typically grouped together in studies assessing surgical interventions or non-operative treatment alternatives. Given the anatomical differences between stenosis affecting the lateral recess or intervertebral foramen, and central canal, the present study elected to separate them into two diagnoses. Interestingly, both groups responded differently to the surgery, with those diagnosed with FS showing superior and sustained clinically important improvements in pain and function, compared to those with CS who were unchanged at each time-point compared to baseline (Figures 7.8-10). Although the limited cases in the CS group restricted the strength of conclusions, the result was interesting and worthy of speculative explanation. It may be argued that the FS categorisation employed in the present study would have benefitted from further separation to distinguish between lateral recess and foraminal cases, given true foraminal stenosis is considered a less common cause of symptomatic nerve root compression (Amundsen et al. 2000; Modic et al. 2005; Tarulli and Raynor 2007).

Perhaps the most fundamental consideration is that FS typically represents a unilateral condition compromising the intervertebral foramen on one side at one segmental level (Modic et al. 2005; Tarulli and Raynor 2007; van der Windt et al. 2010), while CS constitutes more extensive bilateral encroachment on neural tissues at the index level, likely involving a multilevel problem (Kirkaldy-Willis et al. 1978; Yong-Hing and Kirkaldy-Willis 1983). It might also be argued that predominant soft tissue involvement (disc anulus, facet joint capsule and ligamentum flavum) associated with FS (Modic et al. 2005), represents pathology with short term symptoms than might be expected in CS where osseoligamentous remodelling and bony hypertrophy predominate (Kirkaldy-Willis et al. 1978). Unfortunately, the case notes for the subjects employed in the present study, did not include a consistent record for the duration associated with each patient's symptoms, and therefore this speculation is not reasonably corroborated. Although chronicity was assumed in these cases for which surgery was undertaken after at least 12 weeks of symptoms, implicit differences between cases with chronic symptoms exist, and therefore outcomes would reasonably be expected to differ. The time associated with each patient's clinical history before surgery, may be a confounding variable that warrants inclusion in clinical records to allow for cross-sectional data comparisons between cohorts from different studies.

Figure 7.9 showed that all six cases diagnosed with central canal stenosis, were also grouped as having facet pathology. The anterior facet joint capsule is comprised of the ligamentum flavum, which is where significant osseous tissue remodelling occurs in response to aging and degeneration (Yong-Hing et al. 1976; Twomey and Taylor 1988; Giles and Kaveri 1990; Kosaka et al. 2007; Hansson et al. 2009; Kong et al. 2009). Although the LF is essentially soft tissue, cases diagnosed with predominant facet involvement in addition to central canal stenosis, would be expected to show hypertrophied facet joints, and therefore an implied neural tissue encroachment of bony or osseoligamentous origin. In contrast, of the 43 cases diagnosed with foraminal stenosis, the majority (n=28) were categorised primarily with disc pathology, while another four cases with mixed segment disease had a 50% contribution from the disc. Speculatively, intersegmental soft tissue structures are those most likely to be affected by the distraction (although minimal) imposed with insertion of an interspinous device. Consequently, spinal stenosis involving ‘soft’ canal or foraminal compromise due to an infolded ligamentum flavum or protruded posterior disc anulus (Verbiest 1954; Giles and Kaveri 1990; Willen et al. 1997; Kosaka et al. 2007), should be reduced in the presence of an interspinous device. MRI evidence supporting this contention exists, where foraminal and central canal cross-sectional areas are known to increase in the presence of an ISP implant (Richards et al. 2005; Siddiqui et al. 2006a). This rationale may explain why the 28 cases with combined FS and disc pathology in the present series showed the most sustained improvement in back and leg pain out to two years after DIAM-augmented surgery (Figures 7.8 & 7.9). By a similar rationale, it is anatomically reasonable that cases with osseous neural encroachment would require decompression of the offending tissue (and therefore a more extensive surgery) for nociceptive sensitisation to be reduced. Consequently, it appears sound to suggest that LSS (FS and CS) that involves predominant hypertrophic anatomical basis would be reliant on their concurrent decompression techniques employed, perhaps in addition to any ISP device, for success.

Another morphological consideration to explain the superior response in cases with foraminal stenosis as compared with bony central canal stenosis, relates to what constitutes the foraminal or canal borders and space. The intervertebral foramen is defined by the pedicles and articular processes (inferior of the cephalad vertebra, and superior of the caudal vertebra) of two adjacent vertebrae. The anterior and posterior borders are defined by articulations, the interbody and facet joints, respectively. Consequently, the foramen is the sum of two parts with the potential for motion. The same cannot be said for the central canal which comprises a generally bony or osseoligamentous circumferential perimeter. This consideration may identify a need for surgeons to consider the anatomical basis of their patient’s pathology, with cases presenting with soft foraminal or central canal stenosis potentially representing more suitable candidates for DIAM-augmented surgery than those with LSS of an osseous origin. Using a LSS classification system based on symptoms and objective signs, Miyamoto et al (2008) described differing clinical outcomes (determined using the JOA) after nonoperative treatment, between 'radicular', 'cauda equina' and 'mixed' types of LSS patients, with radicular patients responding most favourably to treatment. It may be argued that their radicular and cauda equina classifications (Miyamoto et al. 2008) involved a similar triage to the FS and CS categories used in this thesis, perhaps suggesting that FS cases respond best to treatment.

Recent investigations have shown that patients with LSS caused by degenerative spondylolisthesis do not have a favourable response to ISP-augmented surgery (Verhoof et al. 2008; Richter et al. 2010). The present study also showed a poorer response to DIAM-augmented surgery in the 22 patients with DS as compared to cases with FS. Speculatively, this relates to DS representing a further progression of the degenerative cascade where segmental instability occurs (Kirkaldy-Willis et al. 1974; Kirkaldy-Willis and Farfan 1982). This aspect will be elaborated further in discussing the diagnosis itself, however, the author's contention that LSS be sub-classified to more reasonably compare cases with like pathologies, is supported by this notion. In a recent comparison of DS (n=369) and LSS (n=634) cases from the SPORT trials in the USA, where DS patients were classified based on the presence of listhesis determined from flexion-extension lateral radiographs, a concluding recommendation was not to combine DS and LSS in future studies due to their heterogeneity (Pearson et al. 2010). Although DS and LSS patients had similar characteristics, DS patients improved more with surgery (typically decompression plus instrumented fusion) than LSS patients (typically decompression alone); non-operative outcomes were similar for the two groups. Subgroup classification of LSS may be important in defining suitable patient management.

11.3.2 Disc versus facet pathology

Although this study did not include disc degeneration as a diagnostic category, the anatomical classification used allowed for a distinction between cases with primary (>50%) disc or facet segment disease. Consequently, it is reasonable to distinguish between disc and facet degenerative pathologies based on the results of each of these anatomical groups of cases, both for the retrospective and prospective phases. As reported in Chapter 7, conclusions based on the retrospective phase (Chapter 4) differed from those based on the prospective phase (Chapter 7) in terms of anatomical involvement. Facet cases were shown to have significantly better improvement than disc cases in the retrospective audit, while no significant difference between the two was noted at either one or two years after surgery in the prospective series. However, disc cases in the prospective series had sustained improvement to two years, while facet cases appeared to deteriorate from 6 months, which was also shown for the retrospective cases (Crawford et al. 2009a). Potential explanations for the difference between the findings of the two studies were discussed in Chapter 7, which primarily related to methodological disparity between the two study phases, relative case numbers, and the influences of selection and information bias. That disc cases showed a trend for a sustained response to the surgery may relate to disc pathology potentially being a more discreet problem with easier surgical access and therefore less progressive deterioration postoperatively. The limitation of fewer facet cases (n=10) is acknowledged.

11.3.3 Facet joint pain syndrome

In the surgeon's patient classifications made preoperatively, cases with facet joint pain syndrome were distinct from those with a predominant facet anatomical involvement in their pathology, based on having had a positive (but not sustained) response to facet joint injections applied preoperatively. DIAM-augmented surgery would reasonably be expected to unload the facet joint tissues as has been seen in ex vivo studies (Minns and Walsh 1997, Lindsey et al. 2003, Wiseman et al. 2005). Although primary facet pathology FJPS cases showed improved back pain at all time-points compared to baseline (Figure 7.11), the effect of surgery appeared to diminish from the 3 month postoperative time-point. Leg pain did not respond in these 9 cases however this likely related to variable baseline values. The deterioration may be related to losing the 'correction' of the implant or the soft tissue accommodation to the surgery according to Davis's Law, as speculated earlier. An additional consideration is that by unloading the facet joints with distraction, the imposed local stretch irritates the pain sensitive facet joint capsule and associated soft tissues. As discussed in the section to follow, the unloaded facet joints may allow more translation or torsion at the segment, thereby promoting increased instability and resultant pain. The suitability of DIAM-augmented surgery in the treatment of FJPS, which itself is a somewhat controversial diagnosis based on its myriad influences (Jackson 1992), may require review alongside an improved understanding of the mechanical effect of the device. Investigation with FJPS as a discreet diagnosis would be necessary to provide support for the use of the DIAM in treatment of the condition.

11.3.4 Degenerative spondylolisthesis

Degenerative spondylolisthesis is a complex multifactorial problem representing the clinically broad instability phase of the degenerative spectrum (Kirkaldy-Willis and Farfan 1982). DS generally has a favourable natural history in terms of resolving long term symptoms, as instability decreases with continued progression of normal degeneration secondary to aging (Matsunaga et al. 2000). DS has traditionally been viewed as a diagnostic subcategory of LSS (Arnoldi et al. 1976). The challenge for surgeons tasked with treating the 10-15% cases who progress to surgery after failed non-operative management (Postacchini et al. 1991), is the involvement of both abnormal axial loading and concurrent abnormal positioning at the index segment with DS.

Of the 81 cases examined in the present series, more than one quarter (n=22) were diagnosed with degenerative spondylolisthesis. Diagnosis was based on imaging and the clinical presentation as interpreted by the surgeon; however no formal grading was undertaken to indicate the degree of DS present per case. This may signify a limitation to making assertions regarding the use of the DIAM in treatment of degenerative segmental instability. However, the behaviour of these cases as a group provides insight into DS as a clinical indication for surgery with DIAM. Cases with DS in the prospective phase of the investigation showed no change in primary outcomes when compared to their preoperative baseline. Additionally, cases diagnosed with DS in the prospective phase (n=22 of 81; Figures 7.8-10) and segmental instability in the retrospective series (n=21 of 39; Figure 4.4) had the most variable postoperative response to the surgery (pain and function), as indicated by the spread of data for those cases. This result implies the response to DIAM-augmented lumbar surgery employed to treat DS is not consistent, and therefore its suitability for this clinical indication should be further evaluated.

The development of facet arthrosis and osseoligamentous hypertrophy of the facet capsule, ligamentum flavum, and intervertebral ligaments, is believed to result in secondary stabilisation of the motion segment, thereby preventing progression of the translational slip between vertebrae (Kirkaldy-Willis et al. 1974; Kirkaldy-Willis et al. 1978; Giles and Kaveri 1990; Johnsson et al. 1992; Amundsen et al. 1995; Arbit and Pannullo 2001). Interestingly, none of the 22 cases in the present prospective phase diagnosed with degenerative spondylolisthesis had a predominant facet joint anatomical pathology. This advocates that all the DS cases were in the second stage of instability that preceded restabilisation (Kirkaldy-Willis and Farfan 1982).

The potential for a ‘stabilising’ effect at the index motion segment imposed by the DIAM (or any ISP implant) should be questioned from a fundamental perspective. Patients with DS are reported to have more sagittal orientated (Grobler et al. 1993; Cinotti et al. 1997) or tropic facets (Kalichman et al. 2009b), and although the medial element of their facets prevent shear, the anatomical constraint to slip or translation may be reduced. Further, a recent study reported cases with ‘unstable’ DS to have a wider distance between facet articular processes than ‘stable’ DS cases (Park et al. 2009). In the presence of an ISP device, purported distraction of the posterior elements may result in an even greater capacity for translation due to an increased posterior disc height (Siddiqui et al. 2006b; Sobottke et al. 2009) and reduced apposition of facet joint surfaces (Wiseman et al. 2005). The inherent stability provided by the morphology and close-packed position of the facet joints in erect postures, is potentially compromised by the use of an ISP that is known to unload the facet articulation, particularly in extension. Recent studies have reported poor response to ISP surgery in patients with DS, and it appears an emerging opinion that if ISP implants have a role in DS, they should only be employed in the early instability phase before excessive translation occurs (Verhoof et al. 2008; Lawhorne et al. 2009; Richter et al. 2010). Rigid stabilisation like interbody fusion is arguably more suitable when the capacity for segmental translational motion is more advanced. Four of the 13 failed cases in the prospective series were preoperatively diagnosed with DS; two progressed to ALIF, one to ADR and one had revision of their DIAM (data not shown). Although the proportion of failed DS cases (4 of 22) represented a similar proportion of failures with the diagnosis of FS (7 of 43), the lack or improvement after DIAM surgery in the DS cases implies less benefit in this clinical indication. Further influences on the segmental stability of the vertebral motion segment are discussed in the next section in relation to the surgical technique involved in DIAM implantation.

11.4 Considerations relating to the surgical technique and postoperative course

Aspects of the surgical technique involved in DIAM-augmented surgery are discussed in relation to the clinical outcomes reported in this thesis. Themes include: minimally invasive nature of the surgery, muscle sparing considerations, effect of the surgical incision on segmental stabilisation, DIAM device sizing, potential for device settling, and postoperative rehabilitation after DIAM surgery.

11.4.1 Minimally invasive surgical technique

The presence of approach-related morbidity resulting from iatrogenic muscle and soft tissue injury is a purported motivation for improvements in minimally invasive lumbar surgeries (Jaikumar et al. 2002). Less destructive techniques involving smaller incisions, tissue-sparing and reduced perioperative blood loss, necessitating fewer postoperative narcotics and faster recovery, are applied as an alternative to conventional methods (Fraser and Hall 1993; Chiu 2004; Isaacs et al. 2005; Gibson and Waddell 2007b; Armin et al. 2008; Harrington and French 2008; Kanter and Mummaneni 2008). Surgery with ISP is promoted as a less invasive method to decompression via laminectomy and/or stabilisation with rigid, instrumented fusion (Zucherman et al. 2005a; Hannibal et al. 2006; Senegas et al. 2009). This claim appears reasonable given the extent of excision or disruption of bony tissue (in particular) required for laminectomy and rigid fusion (Bauer et al. 1993). However, limited evidence is available to contrast between surgeries employing ISP devices, and other decompression procedures, which ISPs are more reasonably used to either replace or augment. The results of two ongoing clinical trials (Trials 3&4 presented in Table 2.4) examining decompression procedures as a comparator to ISP, may improve this current information deficit.

Two ‘third-generation’ (Crawford et al. 2009c) ISP devices are implanted percutaneously (PercLID, Superion; Table 2.2), which speculatively represents both device design and surgical technique progressions that are based on minimising tissue destruction. However, few investigations account for outcomes that measure tissue injury after ISP surgery, and those that do, describe the degree of blood loss, postoperative narcotic use, and time spent in hospital, as markers for improvement, particularly for economic analysis. A quantitative index has been recently proposed to characterise the ‘invasiveness’ of spine surgery to allow for safety comparisons (Mirza et al. 2008). Unfortunately, the scoring system does not accommodate ISP surgeries where generally no rigid bony fixation is necessary, rendering ISP surgery to the same category as posterior decompression, and therefore providing inadequate differentiation from the surgeries that ISP devices have been designed to replace or augment.

A finding from the present investigation with relevance to this theme was that cases receiving more than one decompression technique as an adjunct to DIAM insertion, showed superior response to the surgery, than cases receiving a single decompression procedure. As discussed in Chapter 7, it appears critical to examine the influence on outcomes of the variously extensive decompression procedures, such that the need for DIAM (or any ISP) device is better appreciated, if the patient progresses to surgery. The additional expense of introducing the DIAM into the surgical intervention might then be justified based on a proven superiority in response. Interestingly, a recent prospective observational study comparing patient-reported outcomes after two lumbar fusion types that markedly differed in surgical extent and implant cost, showed no appreciable difference in patient reported outcomes between the two surgeries (Grob et al. 2009).

Based on case numbers in the present study, subjects categorised with foraminal stenosis (n=43) were more common than those with central canal stenosis (n=6). Although diagnosis with FS was not qualified by the presence of unilateral or bilateral symptoms, it appears that FS is a more prevalent clinical condition. It might therefore be argued that laminectomy does not represent a suitable comparator in the majority of DIAM spinal stenosis cases. Extensive bony decompression, like removal of the spinous process employed in laminectomy, might be more applicable in cases of central canal stenosis secondary to intra-canal bony encroachment or ossification (Figure 2.4B), than it would be for soft FS where laminotomy and discectomy may be more applicable. Likewise, lumbar fusion may be the most likely surgical alternative for cases with hypertrophied and symptomatic facet joints, which may be a suitable surgical comparator for primary facet-based pathology when decompressive facetectomy is not considered appropriate. It appears critical that clinical outcomes after ISP-based surgeries are matched and compared to their most likely surgical alternative rather than broadly grouping unlike pathologies.

11.4.2 Muscle sparing

Investigators comparing open lumbar surgical techniques with anatomically less destructive methods like: mini-open fusion (Kim et al. 2006a), serial intramuscular dilatation (Fan et al. 2010), percutaneous (Kim et al. 2005), and fluoroscopy-guided paraspinal (Park and Ha 2007) approaches, report superior outcomes in terms of muscle tissue sparing in the cases treated with a less-invasive surgery. Similarly, spinous process splitting decompression techniques are fundamentally centred on limiting iatrogenic muscle injury (Fraser and Hall 1993; Watanabe et al. 2005). Based on MRI studies, Kim et al (2005) confirmed reduced paraspinal muscle strength with concomitant ipsilateral atrophy in cases receiving open compared to percutaneous pedicle screw fixation. Evidence regarding the recovery of back muscles after surgery for low back pain is increasing however the potential postoperative role of myofascial tissues represents an area warranting continued investigation.

No investigation for ISP has reported the effect on local muscle tissues. It would be useful to understand the implication for back muscle tissues in vivo, particularly the deep multifidus and erector spinae groups that are resected and reflected, respectively, between percutaneous (Nardi et al. 2010), SSL sparing (X-Stop or DIAM) or SSL and ISL sacrificing (Coflex or Wallis) ISP surgery approaches (outlined in Tables 2.3&4). As a potential source of symptoms (Bogduk 1983; Groen et al. 1990), back muscle recovery may provide improved understanding of the effect of ISP surgery. This may be particularly relevant given associations between multifidus atrophy and leg pain (Kader et al. 2000), chronic LBP (Danneels et al. 2000; Kulig et al. 2009; Wallwork et al. 2009) and acute LBP (Hides et al. 1994) have been documented. Yet, Kalichman et al (2009) used computed tomography (CT) images from 187 randomly selected cases from a larger cohort being investigated for aortic calcification, to assess the density of subject's paraspinal muscles in relation to self-reported LBP within 12 months, and found no relationship. Interactions between paraspinal muscle density and age and BMI, plus the presence of each of facet joint osteoarthritis, spondylolisthesis and disc narrowing at the same level, were shown (Kalichman et al. 2009a). Denervation and abnormal paraspinal muscle activation were common findings in 25 cases who had not undergone surgery for their LSS, as assessed with electromyography (Leinonen et al. 2003). Pre- and postoperative comparisons of muscle and posterior ligamentous complex tissues in ISP patients may therefore add value in informing clinical pathways. Parameters including fibre type, density, volume/area, and orientation as determined from coronal and sagittal planes, may improve the understanding of the mechanical effect of the device on dynamic tissues.

Medical imaging methods can provide non-invasive, reliable identification of muscle tissues, with a recent progression from using CT to erect MRI (Willen and Danielson 2001; Bearcroft

2007; Chou et al. 2009b). However, the diagnostic capacity of MRI in identifying subtle injury of the posterior ligamentous complex remains less than desirable (Vaccaro et al. 2009). Assessing the lumbar spine under physiological axial load is an attractive option for ISP surgeries given the purported biomechanical effect of the device. Therefore, upright MRI might be the preferred method but may need to be employed with other imaging, like ultrasound (Langevin et al. 2009), to accommodate PLC recovery as well.

11.4.3 Effect of the surgical incision on segmental stabilisation

The potential influence of the surgical incision or DIAM-augmented surgery is discussed in terms of the active and passive stabilising tissues.

Potential influence on active stabilising tissues: Implantation of the DIAM and associated decompressive techniques using a midline surgical incision, requires resection of intersegmental muscles to accommodate the sub-periosteal approach, deep to the base of the spinous process (SP), and laterally along the lamina to the medial margin of the zygapophysial joint (Figure 2.6) (Bauer et al. 1993; Medtronic 2006). Multisegmental muscles are retracted or reflected in the surgery, but ultimately retained (Fraser and Hall 1993). Detachment of MF from the spinous processes and laminae has been shown to result in atrophy and weakness of muscle fascicles, which is believed to contribute to ongoing back pain (Macnab et al. 1977; Sihvonen et al. 1993). Based on their innervation pattern, uni-segmental deep MF fibres are most likely to be affected by resection from the SP, given their local same-segment innervation (Bogduk et al. 1982). Resection or local chemical irritation of multifidus has been shown to interrupt neurovascular supply, risking denervation (Sihvonen et al. 1993; Hodges et al. 2006; Fan et al. 2010). This may represent a problem for the active maintenance of intervertebral segmental stability, speculatively underpinning the reason for the poor response seen in cases with degenerative spondylolisthesis as discussed earlier.

Deep MF fibres are purported to provide segmental stability given their intimate single-segment bridging attachments that approximate the predicted instantaneous axis of rotation (Macintosh et al. 1986; Bogduk et al. 1992; Cholewicki and VanVliet 2002; Jemmett et al. 2004). Superficial MF and other multisegmental groups function to enable motion, particularly encouraging extension of the cephalad vertebra in relation to those more distal (Macintosh et al. 1986; Macintosh and Bogduk 1987; Dolan and Mannion 1994).

Atrophy of lumbar MF is marked by decreased fibre size (Yoshihara et al. 2001; Yoshihara et al. 2003) and the presence of fatty infiltration (Kader et al. 2000; Mengiardi et al. 2006). Asymmetrical MF are shown between sides in acute and chronic low back pain (Hides et al. 1994; Kader et al. 2000; Barker et al. 2004; Hides et al. 2008; Wallwork et al. 2009). Twenty preoperative patients scheduled for microdiscectomy showed reduced CSA of MF at the level of the L4/5 (affected) disc (11.5%, SD 5.6), and more distally local to the irritated L5 nerve root (15.8%, SD 9.5) on the ipsilateral side (Kulig et al. 2009). Kulig et al reported that the average 12.6% reduction in MF area on patient's symptomatic side ($p<0.05$), were identified from MRI by trained radiologists, which has relevance for further research.

Potential influence on passive stabilising tissues: Synergistic load sharing exists between the erector spinae muscles and the viscoelastic elements (dorsolumbar fascia, posterior ligaments, facet joint capsules and posterior anulus) in healthy spines (McGill and Kippers 1994; Solomonov et al. 2003). Potential for altered synergy may occur when either passive, active or neural elements that combine to maintain intervertebral stability are compromised (White and Panjabi 1978; Panjabi 1992; Panjabi 2003). Under static body-weight, intervertebral instability exists in motion segments resected of their musculature, unless intervertebral stiffness is not otherwise increased or replaced (Crisco and Panjabi 1991). Whether distraction imposed by an ISP device can provide suitable passive 'tension' or active stiffness to improve segmental stability is unclear. In addition, potential adaptive shortening of the inter- and supraspinous ligaments might be anticipated in chronic cases that have progressed along the degenerative cascade (Kirkaldy-Willis et al. 1978; Kirkaldy-Willis and Farfan 1982), and therefore any resultant adaptive stiffness may be conceded by puncturing the interspinous ligament for ISP insertion.

The ISL is known to become increasingly tensioned with forward bending (Heylings 1978; Hindle et al. 1990), which is believed to assist the zygapophysial joints in countering the accompanying shear stress during forward motion in the sagittal plane (Yang and King 1984; Putz 1992). In examining the posterior ligamentous complex, Goel et al (1985) reported the supraspinous ligament to experience the greatest force when exposed to flexion across a vertebral segment. Restraint to segmental translation is potentially compromised during forward bending when the ISL is punctured and/or resected during surgical implantation of a DIAM (Medtronic 2006; Taylor et al. 2007). However, in the presence of intact zygapophysial joints, its influence should be minimal, but probably reduced in the case of CS where surgical access is via the facet joint and lamina. In their study examining the influence of the DIAM on six cadaveric specimens, Wilke et al (2008) reported the DIAM to allow more segmental flexion than in the intact state ($p<0.05$) but comparable to the defected state (bilateral hemifacetectomy and ligamentum flavum resection). Increased flexion may lead to more translation or torsion, potentially reducing stability at the segment and increasing reliance on other intact passive and active elements.

11.4.4 Device sizing

The importance of adequate device sizing appears to be emphasised for the application of ISP devices in order to maximise their effect within an individual's anatomical constraint. Recent papers have described the aim of an ISP device to recreate normal interspinous distance and spinal alignment (Cabraja et al. 2009; Kuchta et al. 2009; Sobottke et al. 2009), yet little specific guidance exists to outline what this means for each case. As discussed earlier, results of the present study do not support maximising distraction of the posterior elements because non-responders were cases with the greatest flattening (posterior distraction) of their index disc angle. As only recent literature comparing clinical and radiographic outcomes exist for the DIAM (Kim et al. 2007; Sobottke et al. 2009), it is assumed that the surgical procedural recommendations (Medtronic 2006; Taylor et al. 2007) represent opinions based on the developer's clinical experience.

It might be argued that implantation of the DIAM will always result in implantation with an 'undersized' device given the distracter and inserter tools (illustrated in Figure 2.4) occupy interspinous space during insertion that is subsequently not filled by the device when in situ. This procedural factor may in part explain the potential for device settling as elaborated below. Third generation ISP implants designed with a self-siting and locking mechanism requiring a true unilateral (or percutaneous) insertion that maximises the interspinous distance, like the Impala, In-Space, In-Swing, PercLID and Superion (Figure 2.10) may speculatively (in part) have been designed to mitigate the use of space-occupying implantation tools.

11.4.5 Potential for device 'settling'

Results showed a loss of the imposed segmental kyphosis between the 6 weeks and 12 month postoperative time-points, which had also been identified in the study of Sobottke et al (2009). In Chapter 9, it was speculated that this reversion back to baseline angulation may have been due to settling of the device secondary to the influence of soft and bony tissue accommodation to any imposed new stresses; analogous to stress-shielding. Earlier speculation suggests that there may be an alteration to the IAR after DIAM insertion, which may also require a degree of accommodation to the device. In addition, is the potential for deformation fatigue of the device itself under repetitive axial load; given it comprises silicone as the predominant material. A recent investigation reported erosion of adjacent spinous processes, which conformed to the concavity of the X-Stop ISP device (Miller et al. 2010). This finding substantiates the potential for device settling within the dynamic structure of the vertebral motion segment. It may be reasoned that this would be less likely with a DIAM implant given the relative softness of its primary material. However, settling within the outer bony structure is possible, and combined with a potentially 'under-sized' device at insertion due to the surgical tools, may explain the reversion back to baseline angulation as seen in the present series.

Third generation devices (Table 2.4) appear to have progressed to less dynamic materials (titanium and PEEK), which may have been aimed at mitigating the deformation potential of silicone-based implants. With reports emerging of spinous process (Barbagallo et al. 2009) and bilateral facet fracture (Chung et al. 2009) occurring after (titanium) ISP insertion, the balance necessary in defining what implant is suitable for an individual presentation, appears important.

11.4.6 Postoperative rehabilitation after ISP implant surgery

Spontaneous recovery of MF is not guaranteed once back pain resolves (Hides et al. 1996; Hides et al. 2001), with specific exercises targeting MF deemed useful in promoting episodic and longer term (30 months) recovery (O'Sullivan et al. 1997; Hides et al. 2001; O'Sullivan 2004). According to Dolan et al (2000), undertaking a four week postoperative exercise programme commencing at six weeks after microdiscectomy surgery, results in superior improvements in pain, disability, back muscle endurance and hip and lumbar mobility, than cases receiving the surgery accompanied with postoperative functional advice only, with improvements maintained at 12 months (Dolan et al. 2000). A Cochrane review reporting on rehabilitative exercise after lumbar disc surgery, described faster improvements in pain and function in patients who undergo postoperative exercises (starting from 4-6 weeks after surgery) compared to non-exercisers receiving the same surgery (Ostelo et al. 2009). Similarly, recent guidelines from the American Pain Society have promoted an interdisciplinary rehabilitation approach to the treatment for low back pain, to be inclusive of the patient in shared decision-making (Chou et al. 2009c). It might be argued that an integrated combination of surgery aimed at the passive structures, and postoperative exercises targeted to restore muscle function and improve motor control, would represent an improved approach to treatments employing ISP devices. The patients followed in this thesis all underwent a postoperative exercise-based rehabilitation programme as routine postoperative protocol, so it may be argued they received adequate attention to passive and active stabilisers. The rehabilitation aspect of a patient’s management after DIAM surgery is not well defined and was not the focus of the current investigation. However, such a survey appears warranted to improve postoperative management guidelines for ISP surgeries in order to maximise patient recovery.

11.5 Summary

The prospective phase of this thesis assessed clinical outcomes in 81 subjects over a two year period of observation after lumbar surgery augmented with DIAM. Patient-reported HRQoL outcomes demonstrated clinically significant improvement in back pain, leg pain and function, which was shown at all time-points compared to preoperative baseline. However, the level of improvement, declining patient satisfaction with symptoms, increase in non-responders at two years and a relatively high reoperation rate, did not indicate a change considered meaningful to patients. Responder analyses revealed that cases with foraminal stenosis experienced the best improvement, while those with degenerative spondylolisthesis had the worst response. The heterogeneous and highly selected cohort made conclusions difficult and further investigation controlling for confounders, like the adjunctive decompression procedures, is necessary to confirm study findings.

A small segmental flattening of the index disc angle (measured via radiography) and the lumbar depth (measured from the skin surface via rasterstereography) was shown in the early postoperative period, but returned to baseline by 12 months after surgery. No other measureable change in spinal curvature was noted over the period of observation. Responder analysis indicated that subjects with a preoperative lumbar sagittal alignment behind the vertical axis, or cases with the most flattening of the disc angle at 6 weeks after surgery, were less likely to respond. Responders tended to straighten their thoracolumbar spine initially, but revert back to their preoperative posture. Although an early segmental kyphosis was confirmed in the presence of the DIAM, the biomechanical effect of the device is questioned. An altered axis of rotation and related soft tissue adaptation may provide reasonable rationale for the study observations. Only weak associations between subjective and objective outcome variables were shown, making it difficult to provide guidance for surgeons with respect to the mechanical aims of DIAM-augmented surgery.

This main discussion has considered each relevant diagnostic category based on considerations relating to the surgical technique, and concluded that foraminal stenosis represents the clinical indication most likely to respond favourably to DIAM-augmented decompression surgery. Alternative surgeries for cases with degenerative spondylolisthesis should be considered in light of the poor response in DS cases reported in this study where the capacity for DIAM surgery to restore stability appears limited.

CHAPTER 12

Conclusions and Recommendations

12.1 Conclusions

This observational longitudinal cohort study was conducted to test the main hypothesis that lumbar surgery augmented with the DIAM interspinous implant resulted in clinically significant improvement in patient-reported outcomes, which related to a minimally altered segmental vertebral alignment. Eighty-one patients were enrolled in the prospective study as individuals receiving DIAM-augmented surgery from a single private neurosurgical practice in Perth, Western Australia.

Surgical cohort: The main study conclusions relating to the surgical cohort are summarised as follows according to the respective hypotheses reported in Chapter 3.3:

1. The results of the present investigation confirm the primary hypothesis that lumbar surgery augmented with a DIAM interspinous stabilisation device results in clinical improvement in back and leg pain and function at all time-points out to 24 months compared to preoperative baseline. However, based on criteria described by Dworkin et al (2008) and Ostelo et al (2008), improvements were only minimal and not clinically important or meaningful to patients. Greatest improvement occurred by the 3 month postoperative period and showed a gradual deterioration out to two years after surgery, but remained significantly better than preoperative values.

2. The results of the present investigation reject the hypothesis that patients with primary zygapophysial joint anatomical involvement would show superior improvement than cases with disc or combined disc-facet segment disease. Primary disc cases showed a trend for better improvement in leg pain postoperatively, but the difference compared to primary facet disease cases was not statistically significant.

3. The results of the present investigation confirm the hypothesis that no change to surface thoracolumbar curvature, as determined via rasterstereography, occurred after surgery augmented with DIAM interspinous implant over a two year time course compared to baseline. However, there was an appreciable mean reduction in the depth of the lumbar curvature for the group of cases assessed, which occurred in the first six week postoperative period. Lumbar depth had reverted back to baseline values by the 6 month postoperative stage.

4. The results of the present investigation confirm the hypothesis that a small relative segmental kyphosis occurred at the primary level of DIAM implantation at six weeks postoperatively, as determined through radiographic analysis. This segmental flattening was not maintained out to one year postoperatively.

5. The results of the present investigation confirm the hypothesis that skeletal regional lumbar curvature does not change after surgery augmented with DIAM interspinous implant at any stage over one year compared to baseline.

In addition to the main hypotheses relating to the surgical cases, the present study also documented the following findings:

(i) Response to DIAM-augmented surgery in terms of back pain, leg pain and function, declined between the one and two year postoperative time-points.

(ii) Cases diagnosed with foraminal stenosis had superior response in leg pain improvement compared to central canal stenosis ($p<0.05$), facet joint pain syndrome ($p<0.01$) and degenerative spondylolisthesis ($p<0.0001$); degenerative spondylolisthesis cases showed less improvement than cases with foraminal stenosis for back pain ($p<0.05$), leg pain ($p<0.0001$) and function ($p<0.0001$).

(iii) Cases receiving more than one adjunctive decompression procedure responded better than those receiving a single decompression technique in addition to their DIAM ($p<0.05$).

(iv) Back pain responders showed an early thoracolumbar postural straightening, which differed from non-responders whose thoracic and lumbar curvatures subtly increased ($p<0.05$).

(v) Non-responders in terms of back pain and function had a negative skeletal lumbar sagittal balance preoperatively ($p<0.05$) and showed more early (6 weeks) flattening at the primary disc angle ($p<0.05$).

(vi) Generally no significant associations were shown between variables of surface and skeletal spinal curvature. Surface lumbar lordosis and skeletal radius of curvature showed a weak relationship ($r=0.35$, $p<0.05$). Early change in lumbar lordosis determined from the skin surface and skeletally, were weakly related ($r=0.36$, $p<0.05$). A moderate association was seen between the change in surface and skeletally-derived sagittal balance ($r=o.50$, $p<0.01$).

(vii) When baseline sagittal balance and early change in primary disc angle as derived from radiographs were compared, the association was moderate in back pain non-responders ($r=0.62$, $p<0.001$), while no relationship was shown for responders.

Healthy volunteers: The main study conclusions relating to the healthy volunteers are summarised as follows (numbered according to the hypotheses reported in Chapter 3.3):

6. The results of the present investigation confirm the hypothesis that no change to surface lumbar lordosis or thoracic kyphosis, as determined via rasterstereography, occurred at any time-point in healthy volunteers over a two year time course. However, pelvic incidence and sagittal balance were variable within the two year period but remained the same at two years compared to baseline.

7. The results of the present investigation confirm the hypothesis that variability (although not consistent) in thoracolumbar sagittal balance, as determined via rasterstereography, in healthy volunteers of a wide age range existed within and between individuals.

In addition to the main hypotheses relating to the healthy cases, the present study also documented the following findings:

(i) Gender differences in lumbar lordosis, pelvic incidence and thoracolumbar sagittal balance were observed, with no difference noted for thoracic kyphosis: Lumbar lordosis and pelvic incidence were greater in women than men; sagittal balance was more positive in women.

(ii) Strong and moderate relationships were found between pelvic incidence and sagittal balance, and lumbar lordosis and thoracic kyphosis, respectively.

Additional methodological conclusions were:

3.1 Reproducible measurement [mean SD; mean CV%] of lumbar lordosis was derived from rasterstereographic back shape imaging of a thermoplastic back phantom [0.14˚; 0.6%], healthy volunteers [1.1˚; 2.4%] and lumbar surgery patients [0.9˚; 1.8%] spanning a wide age range.

4.1 Measurements of segmental spinal curvature based on digital plain radiographic images were sensitive to change [mean△; SD△] in variables of skeletal lumbar curvature: lumbar lordosis [-0.15˚; 2.3˚], sacral inclination [0.07˚; 1.6˚], primary disc angle [0.50˚; 1.1˚] and lumbar sagittal balance [0.31˚; 1.9˚].

12.2 Recommendations for Future Study

Due to the limited sample size and the cross-sectional nature of this prospective observational longitudinal study, the findings may be used to generate hypotheses for larger studies. The predictive power of the multiple comparisons will need to be established in larger studies using a responder analysis approach, where absolute and normalised percentage improvement from baseline values are considered alongside MID recommendations. Assessing patients who under-report or report low baseline levels, but who have the potential to achieve complete relief of their disabling symptoms, should be integrated into follow-up, to reflect the clinical reality. Excluding them based on low baseline pain and function (<30%) in order to meet appropriate absolute MID change scores, does not allow for guidance to surgeons for whom these patients have sought treatment. As such, the longitudinal observational design employed in the thesis is appropriate to establish the effectiveness of the device across its wide application. However, recruiting adequate case numbers across each diagnosis to afford suitably powered comparisons is important. This may be difficult for the less common diagnostic categories like central canal stenosis and facet joint pain syndrome. Sample size calculations based on conventional levels of significance (5%) and power (80%) for clinical trials (Kirby et al. 2002; Wittes 2002), and using the MID recommendations (Dworkin et al 2008, Ostelo et al 2008) for clinically meaningful difference in pain (20-30%) and function (15-30%), should be adopted depending on the intended statistical tests. For example, comparison of mean improvement in pain or function would require samples of 32 cases for each diagnosis.

Collaboration of Australian-based surgeons, academic institutions and treatment facilities performing ISP (and other spine) surgeries, in a national or international observational spine registry [e.g.: the Spine Tango network (Melloh et al. 2008)], should be promoted in order to improve the opportunity for data pooling and comparisons between surgeries or interventions aimed at treating the same pathological conditions. The use of standardised outcome instruments and objective patient categorisation methods (Zweig et al. 2009) may allow for improved collaboration between centres, particularly for smaller facilities where patient numbers are fewer and the capacity for adequately powered studies is consequently compromised. For an observational spine registry to be a useful instrument in compiling data for later research or cohort comparisons, successful implementation is reliant on motivated multidisciplinary users with an appreciation of its potential long term value, and an undertaking to objectively record detailed patient information (Zweig et al. 2009). Based on their experience with the Spine Tango registry, Melloh et al (2008) indicate that voluntary participation rates and the representativeness of registered data, may improve with the application of binding rules for documentation and associated monitoring mechanisms. Potential variability in the fidelity of registered data presents a limitation to studies performed on the basis of 'registered' data.

Matured validating processes may mitigate the prevalence of unreliable reporting.

Comparisons of DIAM-augmented surgeries to decompressive surgery alone, should be vigorously pursued in order to better identify any benefits of employing the device over its more economical and increasingly used alternative (un-instrumented decompression) (Melloh et al. 2008). Attention to the natural history of lumbar degenerative diseases in the aging population should be made, particularly given evidence indicating that spinal decompression or fusion surgeries may not be superior to the natural course of the disease (Johnsson et al. 1992; Amundsen et al. 2000). The continuing introduction of new and purportedly improved ISP devices into the spinal surgery market arguably confuses a surgeon's clinical reasoning process for appropriate patient selection. This is particularly so when differentiation of ISP surgery from an apparently widening variety of minimally invasive and less destructive decompression or fusion techniques (Armin et al. 2008; Liu et al. 2008; Mirza et al. 2008; Hatta et al. 2009; Deyo et al. 2010; Shetty et al. 2010) is based on limited published comparison studies. The results recently reported by Richter et al (2010) indicate no additional benefit to employing the Coflex device with decompression surgery in LSS. Ongoing clinical trials are examining clinical outcomes after surgery with two third generation (Superion Spacer, In-Space Interspinous Distraction Device) versus a second generation ISP (X-Stop) implant [Table 2.4; (Crawford et al. 2009c)]. However, results of these two studies are still pending. Exploration of the Spine Tango registry may reveal suitable ISP cohorts given certain ISP technologies were developed and popularised initially in Europe. A case-control study that randomly allocates patients into decompression alone, or decompression plus DIAM surgery would be an appropriate study design. Identifying the most suitable comparator control group [like microdiscectomy (for FS secondary to HNP), or laminotomy (for CS)] should be emphasised in relation to the specific diagnostic category for which DIAM-augmented surgery is rationalised. Additionally, given that the DIAM (or other ISP devices) may be implanted in isolation without a decompression procedure, it appears reasonable that a DIAM alone cohort be compared with a DIAM plus decompression group, with patients of a defined diagnosis (like foraminal stenosis), randomly allocated to each treatment. It is acknowledged that the DIAM is more commonly used as an augmentation to other lumbar procedures; hence recruiting an adequate sample size may prove difficult.

Another reported indication for the application of an ISP, is as an adjunct to rigid instrumented fusion at the supradjacent level. This thesis did not examine this indication; however a recent study has shown benefit of the Wallis ISP in reducing adjacent segment degeneration above lumbosacral instrumented fusion (Korovessis et al. 2009). Therefore, 'topping-off' should be factored in to future studies as a potential indication, such that the application of ISP technologies is comprehensively defined. The results of the present thesis indicated that the

DIAM had no influence on the supradjacent disc angle, despite an early relative kyphosis at the index level. This result may be considered encouraging in relation to the potential for the DIAM to complement rigid fusion surgery, although as disc degeneration typically presents some time after rigid fusion, conclusions based on the present series may be premature.

Extending the follow-up of the present series beyond the two year postoperative period, may better determine any significance of the trend for deterioration in back pain, leg pain and function seen toward the two year time-point. In their study examining patients with lumbar spinal stenosis for ten years after either surgical or conservative treatment, Amundsen et al. (2000) showed no clinically significant deterioration in the last six years. Their results agreed with those of Johnsson et al (1992) who observed the natural course of 32 LSS patients for a mean of 4 years, and showed that the majority (85%) were either unchanged (70%) or better (15%); only 15% had naturally worsening symptoms. Extending the follow-up of the current series to at least the four year postoperative time-point would therefore be of benefit.

Reporting the anatomical basis for pathology in ISP-related (and other spinal) research, particularly given the somewhat broad and variable definitions for each clinical condition, may provide a suitable delineation between diagnoses. As shown throughout this thesis, the best example of the need for improved distinction between pathologies relates to lumbar spinal stenosis, which comprises a range of clinical presentations including bilateral or unilateral back, buttock or leg pain, neurogenic intermittent claudication, radicular symptoms, and movement-related segmental instability, in combination or isolation. Distinction between central canal and lateral recess or foraminal stenosis represents an anatomically specific yet suitably wide categorisation, which may better align with patient symptoms. Although surgical treatments would intend to alleviate all symptoms, effectively rendering their source less important, more specific anatomical considerations might assist with patient selection and surgical planning. The author acknowledges that in reality the clinical conditions treated with the DIAM implant reflect a greyscale and consequently, a proposal to sub-analyse them may not be workable given sample-size limitations for such discrete diagnoses. However, based on the results of the present study where foraminal stenosis cases with primary disc involvement showed a trend for superior improvement compared to FS cases with primary facet involvement, establishing the distinction between the two for the application of DIAM-augmented surgery appears important.

The present investigation relied on the surgeon's diagnostic categorisation of patients, which, while based on imaging, patient response to interventional treatments and their clinical presentation, were not strictly referenced to a graded extent of anatomical involvement. The radiographic magnification concerns in the study contributed to the difficulty in doing so. In making the distinction between foraminal and central canal stenosis, and degenerative spondylolisthesis, it may be advisable to indicate the extent of the pathology. Lateral recess and central canal diameter, foraminal area, and grade of segmental slip or translation would provide a suitable basis. Similarly, the extent and site of tissue removal in the adjunctive decompression procedure may also warrant formal recording. Also on the anatomical theme, Barbagallo et al (2009) showed that spinous process fracture or X-Stop device dislocation may be a consequence of incompatible interspinous and spinous process morphology. They noted a convex inferior border of the spinous process in patient's who experienced a dislocated device (associated with supraspinous ligament rupture) or spinous process fracture. The preoperative distance between spinous processes may also be an indicator of successful use of an ISP device, particularly in identifying Baastrup's disease (interspinous bursitis), which may be a comorbidity to LSS (Maes et al. 2008) that has the potential to influence outcomes after ISP implantation.

The present study did not separately assess subjects using a global rating scale, depression index or preoperative expectations questionnaire, all of which have been shown to be predictive of outcome, as indicated in Chapter 11. The additional inclusion of a body chart to better define the distinction between back and leg pain, particularly in relation to the buttock region, may be of benefit. These outcome measures could be a valuable addition to future research, however, being conscious of limiting responder burden by providing a concise outcome tool, should be a priority. In addition to assessing patient-reported back related function using the ODI, objective evaluation of disability and physical impairment, like the walk test (Barz et al. 2008) or active range of motion (Waddell et al. 1992; Amundsen et al. 1995), may provide an improved appreciation of prognosis and postoperative outcomes.

Further study investigating skeletal curvature in vivo over an extended time frame and at several time-points would allow for elaboration of the radiographic findings shown in this investigation. However, the ethical implications of repeat ionising imaging could be restrictive. MRI performed in standing may provide a more suitable alternative for serial assessment of skeletal and surface spinal curvature, particularly in the early postoperative period where soft tissue healing occurs. Changes in the dynamic structures, like muscle and ligamentous tissues that are potentially affected by the presence of an ISP device, would arguably be more realistically appreciated in axial loaded conditions. This may contribute to identifying any critical stage in the segmental effect of an interspinous device, particularly when postoperative soft tissue healing can be examined in relation to any change in spinal alignment. The issue of device-settling might therefore be better understood. In addition, the postoperative recovery of associated soft tissues that were purportedly tensioned with the surgery, like the posterior disc anulus, ligamentum flavum and facet joint capsules, might also be monitored for change. This may be particularly so when a degree of preoperative viscoelastic adaptive shortening and postoperative creep in the presence of the device, might be expected over time. However, the subtly of adaptation in these structures may be close to the measurement error in attempting to capture their change and therefore only inferences regarding their recovery would be possible. The consequence of lumbar surgical approaches on lumbar region muscles, like the erector spinae and particularly multifidus, may represent an additional area for future evaluation after ISP-based surgery, wherein iatrogenically injured or potentially denervated muscle fibres might be monitored. Studies employing upright MRI may offer novel insight into outcomes after lumbar surgery with DIAM (or other ISP devices) wherein sagittal and coronal planes can be monitored.

Limited MRI facilities in Australia that have the capacity to image patients in upright axial-loaded postures (one centre in New South Wales), arguably detracts from the ability of researchers in this country to lead investigative endeavours into spine-related pathologies, where safe and effective monitoring of morbidity and mortality is of high priority. Evaluation of patients in functional and relevant postures, could contribute to an improved appreciation of impairment and disability in patients, particularly for those with chronic conditions relating to the aging process.

Studies based on radiographic imaging in vivo, particularly those hypothesising subtle changes in spinal alignment, should integrate a radio-opaque magnification reference to allow for normalised serial comparisons. This step should be employed in addition to using well-defined, standardised protocol, including patient positioning requirements, particularly when various radiography centres are being used. To measure and accommodate the effects of postural sway, chiefly when measuring spinal curvature variables that reference the vertical (like sagittal balance), concurrent use of force-plate technologies may be of value. Inclusion of imaging that allows for measurement of regional and segmental motion of the lumbar spine in vivo (like flexion-extension images) may improve the understanding of the purported motion-preserving nature of an ISP device.

12.3 Summary

This chapter has presented the main and secondary conclusions of this thesis in relation to the surgical cases, healthy volunteers and methodological aspects of the investigation. While the presented conclusions offer a contribution to narrowing the clinical indications for employing the DIAM, distinction between outcomes attributed to adjunctive decompression procedures or disease natural history remain ill-defined. Recommendations for future research are made based on the continued need to better understand the effectiveness of the DIAM in the treatment of lumbar spinal disease.

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APPENDIX I.1

INFORMATION SHEET

Retrospective review of clinical outcomes following lumbar spine surgery

Evaluating clinical outcomes following lumbar spine surgery provides insights into the efficacy of these procedures. In collaboration with Mr Quentin Malone, neurosurgeon, we are seeking your permission to review clinical records associated with your recent spinal operation. In particular we wish to examine the imaging reports, clinical notes and MODEMS questionnaires that you have completed over time. This retrospective review is intended to assist us as we develop new questionnaire instruments to more efficiently collect follow-up data from patients who undergo these procedures in the future.

This information would be summarised for a research thesis being undertaken at UWA and may also be used in publications. However, all recorded material would be de-identified so that the collected data would be anonymous. You are free to withdraw your permission at any time and without prejudice to any future treatment.

Should you have any questions or request further information about this review please contact Mr Malone at his rooms on 9486 4780.

Professor Kevin Singer - Chief Investigator, Centre for Musculoskeletal Studies, School of Surgery and Pathology, The University of Western Australia., L2 Medical Research Foundation Building, Royal Perth Hospital. Dr Singer may be contacted at UWA on 9224 0200. Alternatively you may contact Rebecca Crawford (PhD postgraduate student/investigator) at UWA on 9224 0215.

This retrospective review of clinical records has been approved by the Human Research Ethics at The University of Western Australia [RA: 4/1/1743]

THE UNIVERSITY OF WESTERN AUSTRALIA

FACULTY OF
Medicine, Dentistry and Health Sciences

CONSENT FORM

Retrospective review of clinical outcomes following lumbar spine surgery

Evaluating clinical outcomes following lumbar spine surgery provides insights into the efficacy of these procedures. In collaboration with Mr Quentin Malone, neurosurgeon, we are seeking your permission to review clinical records associated with your recent spinal operation. In particular we wish to examine the imaging reports, clinical notes and MODEMS questionnaires that you have completed over time. This retrospective review is intended to assist us as we develop new questionnaire instruments to more efficiently collect follow-up data from patients who undergo these procedures in the future.

This information would be summarised for a research thesis being undertaken at UWA and may also be used in publications. However, all recorded material would be de-identified so that the collected data would be anonymous. You are free to withdraw your permission at any time and without prejudice to any future treatment.

I ___________________________________ have read the information provided and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason and without prejudice to my future treatment).

I understand that all information provided is treated as strictly confidential and will not be released by the investigator. The only exception to this principle of confidentiality is if a court subpoenas documentation. I have been advised as to what data is being collected, what the purpose is, and what will be done with the data upon completion of the research.

I agree that research data gathered for the study may be published provided my name or other identifying information is not used.

_____________________   ___________________

Signature   Date

The Human Research Ethics Committee at the University of Western Australia requires that all participants are informed that, if they have any complaint regarding the manner in which a research project is conducted, it may be given to the researcher or, alternatively to the Secretary, Human Research Ethics Committee, Registrar's Office, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009 (telephone number 6488-3703). All study participants will be provided with a copy of the Information Sheet and Consent Form for their personal records.

This retrospective review of clinical records has been approved by the Human Research Ethics at The University of Western Australia [RA: 4/1/1743]

APPENDIX I.2

SUBJECT INFORMATION

Evaluating clinical outcomes following lumbar spine surgery

Evaluating clinical outcomes following lumbar spine surgery provides insights into the efficacy of these procedures. Following an invitation from Mr Quentin Malone, your neurosurgeon, we are now seeking your permission to review the clinical records associated with your recent low back pain and subsequent neurosurgical consultation(s). We wish to follow-up your case from your initial visit with Mr Malone and for a period of approximately 2 years thereafter. We will examine your imaging reports, clinical notes and associated questionnaires over that time. The questionnaires may be completed in paper format or by logging onto a website using a unique password. We will use a back-shape video analysis system to record your spine posture pre- and postoperatively.

For this prospective study we would like to assess your back posture as an adjunct to your ongoing routine physical assessment. This will involve taking a video image of your back using a computerised back shape assessment system. This back shape system is being evaluated as a complementary method to radiographic examination. You will be asked to assume a normal standing posture with your back towards a camera and projector. The photograph will capture an image of your spine from the base of your neck to the base of your low back. It will only take a few seconds. You will need to be appropriately disrobed and therefore an open-backed hospital gown will be provided for you. Testing will be carried out in the MRF Building adjacent to Royal Perth Hospital and will be supervised by an experienced research physiotherapist.

The information sought from this study will be summarised for a research thesis being undertaken at UWA and may also be used in publications. However, all recorded material would be de-identified so that the collected data would be anonymous. You are free to withdraw your permission at any time and without prejudice to any future treatment.

Should you have any questions or request further information about this study please contact Mr Malone at his rooms on 9486 4780, or contact me at UWA on 9224 0200.

Professor Kevin Singer - Chief Investigator, Centre for Musculoskeletal Studies, School of Surgery and Pathology, The University of Western Australia, L2 Medical Research Foundation Building, Royal Perth Hospital.

This review of clinical records has been approved by the Human Research Ethics at The University of Western Australia [RA/4/1/1766]

THE UNIVERSITY OF WESTERN AUSTRALIA

FACULTY OF Medicine, Dentistry and Health Sciences

CONSENT FORM

Evaluating clinical outcomes following lumbar spine surgery

Evaluating clinical outcomes following lumbar spine surgery provides insights into the efficacy of these procedures. Following an invitation from Mr Quentin Malone, your neurosurgeon, we are now seeking your permission to review the clinical records associated with your recent low back pain and subsequent neurosurgical consultation(s). We wish to follow-up your case from your initial visit with Mr Malone and for a period of approximately 2 years thereafter. We will examine your imaging reports, clinical notes and associated questionnaires over that time. We will use a back-shape video analysis system to record your spine posture pre- and postoperatively.

This information would be summarised for a research thesis being undertaken at UWA and may also be used in publications. However, all recorded material would be de-identified so that the collected data would be anonymous. You are free to withdraw your permission at any time and without prejudice to any future treatment.

I ___________________________________ have read the information provided and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason and without prejudice to my future treatment).

I understand that all information provided is treated as strictly confidential and will not be released by the investigator. The only exception to this principle of confidentiality is if a court subpoenas documentation. I have been advised as to what data is being collected, what the purpose is, and what will be done with the data upon completion of the research.

I agree that research data gathered for the study may be published provided my name or other identifying information is not used.

______________________ ___________________

Signature Date

The Human Research Ethics Committee at the University of Western Australia requires that all participants are informed that, if they have any complaint regarding the manner in which a research project is conducted, it may be given to the researcher or, alternatively to the Secretary, Human Research Ethics Committee, Registrar's Office, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009 (telephone number 6488-3703). All study participants will be provided with a copy of the Information Sheet and Consent Form for their personal records.

This review of clinical records has been approved by the Human Research Ethics at The University of Western Australia [RA/4/1/1766]

THE UNIVERSITY OF WESTERN AUSTRALIA

Research Ethics
Research Services
M459

35 Stirling Highway, Crawley, WA 6009
Telephone: (08) 6488 3703
Facsimile: (08) 6488 8775
Email: kkirk@admin.uwa.edu.au
http://www.research.uwa.edu.au/human_ethics

Our Ref. RA/4/1/1743

7 March 2007

Professor K Singer
Centre for Musculoskeletal Studies - M572
RPH

HUMAN RESEARCH ETHICS COMMITTEE

Project: **Retrospective review of clinical outcomes following lumbar surgery**
Student: **Rebecca Crawford - PhD - 18813148**

Please be advised that ethical approval of the above project has been granted by the Human Research Ethics Committee.

The Committee is bound by NHMRC Guidelines to monitor the progress of all approved projects until completion to ensure that they continue to conform to approved ethical standards.

The committee requires that all Chief Investigators report **Immediately** anything that might affect or impact upon ethical approval of the project, including adverse events affecting subjects.

Approval should be sought in writing **in advance** for any amendments to the original application. You are also required as a condition of this approval to inform the Committee if for any reason the research project is discontinued before the expected date of completion.

A report form for completion will be sent to you twelve months from this date or one month after your indicated completion date.

Please note that approval has been granted for a period of four years. Initial approval is for a period of one year, and, thereafter for future periods of one year at a time subject to the receipt of satisfactory annual reports. At the end of the four-year period you will be required to complete a new "*Application to Undertake Research Involving Human Subjects*" should you wish to continue with your research. However, in special circumstances, the Chair has the authority to extend the approval period in order to complete a project.

Please quote Project No RA/4/1/1743 all correspondence associated with this study.

Yours sincerely

KATE KIRK
Executive Officer
(Human Research Ethics Committee)

APPENDIX II.2

THE UNIVERSITY OF WESTERN AUSTRALIA

Research Ethics
Research Services
M459

35 Stirling Highway, Crawley, WA 6009
Telephone: (08) 6488 3703
Facsimile: (08) 6488 8775
Email: kkirk@admin.uwa.edu.au
http://www.research.uwa.edu.au/human_ethics

Our Ref. RA/4/1/1766

11 April 2007

Professor K Singer
Centre for Musculoskeletal Studies - M572
RPH

HUMAN RESEARCH ETHICS COMMITTEE

Project: **Prospective review of clinical outcomes following lumbar surgery**
Student: **Rebecca Crawford - PhD - 18813148**

Please be advised that ethical approval of the above project has been granted by the Human Research Ethics Committee.

This project is approved on condition that the Consent Form contains a statement reading "I agree to the researchers having access to my medical records held by Mr Quentin Malone."

The Committee is bound by NHMRC Guidelines to monitor the progress of all approved projects until completion to ensure that they continue to conform to approved ethical standards.

The committee requires that all Chief Investigators report **immediately** anything that might affect or impact upon ethical approval of the project, including adverse events affecting subjects.

Approval should be sought in writing **in advance** for any amendments to the original application. You are also required as a condition of this approval to inform the Committee if for any reason the research project is discontinued before the expected date of completion.

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Please quote Project No RA/4/1/1766 all correspondence associated with this study.

Yours sincerely

KKirk

KATE KIRK
Executive Officer
(Human Research Ethics Committee)

Cc: Dr Sato Juniper

APPENDIX III.1

'DIAM' CHECKLIST

Patient details/sticker

For Patient:

- ☐ Prospective review UWA patient consent form
- ☐ Prospective review UWA patient information form [**Retain to file**]
- ☐ Web link or paper outcomes questionnaire (baseline and follow-ups)
  - o Web address & password
- ☐ Standing lateral x-ray referral pre-signed (baseline, 6 weeks post-op, 12 months post-op) with radiographer guideline attached
- ☐ Back curvature referral pre-signed (to reflect x-ray (&other) timeframes)

Date	Timeframe	Xray Ref	Raster Ref	Q'aire	UWA consent
	Baseline	☐	☐	☐	☐
	6 weeks	☐	☐	☐	
	3 months			☐	
	6 months		☐	☐	
	12 months	☐	☐	☐	
	18 months		☐	☐	
	24 months		☐	☐	

For Dr Malone

- ☐ Diagnosis categorization form (baseline)

APPENDIX III.2

REVIEW OF CLINICAL OUTCOMES FOLLOWING LUMBAR SURGERY (DIAM)

DIAGNOSIS CATEGORISATION

Patient Name: ______________________________ Surgery Date: ____________________

ANATOMICAL INVOLVEMENT (PRIMARY)

1. DISC
2. FACET
3. MIXED (BOTH EQUALLY)

DIAM REASONING

1. FACET UNLOADING
2. INSTABILITY
3. NERVE ROOT COMPRESSION
4. CANAL STENOSIS

SINGLE LEVEL (PRIMARY) LEVEL(S)		SECONDARY	
L1-2	☐	L1-2	☐
L2-3	☐	L2-3	☐
L3-4	☐	L3-4	☐
L4-5	☐	L4-5	☐
L5-S1	☐	L5-S1	☐

COMORBIDITIES

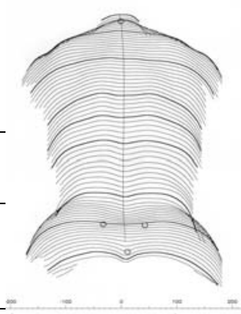
List those relevant:

____

____

APPENDIX IV.1

BACK SHAPE ANALYSIS REFERRAL



Thank you for providing back shape analysis of lumbar curvature for:

Name: ______________________________

DOB: ______________________________

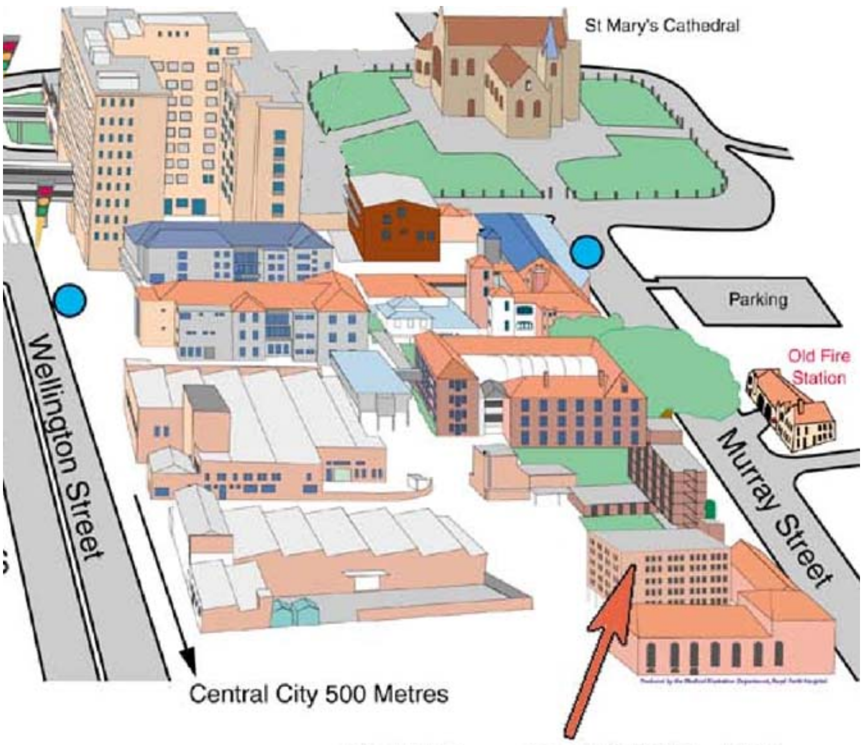
____

Mr. Quentin Malone
Centre for Neurological Surgery
34 Ord Street, West Perth WA 6005

Patient Information:
To schedule an appointment please contact: Ms Rebecca Crawford
Centre for Musculoskeletal Studies., UWA, on Tel: 9224 0215
Address: Level 2, [Surgery], Medical Research Foundation Building
Royal Perth Hospital
Rear entry at 50 Murray Street, Perth 6000 *[please refer to map]*

Your low back curvature from a relaxed standing position will be measured using a specialized video system. The procedure takes no more than 5 minutes. You will be asked to undress to your underwear in a darkened room. Your modesty will be respected. This investigation will be used to examine for changes to your posture before and after low back surgery. Formal Ethics approval for this study has been obtained from UWA. The procedure will be explained fully and your questions answered before this study is performed.

Thank you for your cooperation and interest.



CMS Level2, MRF Building

STANDING LATERAL RADIOGRAPH LUMBAR SPINE

FOR: Mr. Quentin Malone, Neurosurgeon

34 Ord St, West Perth WA 6005

<u>PATIENT POSITIONING GUIDELINES</u>

To the Radiographer
Thank you for using the following patient protocol.

Patient is to assume a relaxed standing position with the arms in the ‘clavicle position’ as illustrated. Elbows are fully flexed with hands placed into the supraclavicular fossae. The arms are not crossed and there is no external support.

100cm film-tube distance – unless patient is large

L3 centred (as able); Consistent L or R-side stance

Please ensure the lumbar spine / pelvis is not side-flexed either toward or away from the buckey.

Thank you for your cooperation.

APPENDIX V

Clinical outcomes after lumbar surgery

HEALTH QUESTIONNAIRE

Would you please complete this questionnaire. It is designed to give us information as to how your back (or leg) trouble has affected your ability to manage in everyday life.

Please answer every section. **Mark one selection only** in each section that most closely describes you **today**.

Section 1: Pain Intensity
- o I have no pain at the moment
- o The pain is very mild at the moment
- o The pain is moderate at the moment
- o The pain is fairly severe at the moment
- o The pain is very severe at the moment
- o The pain is the worst imaginable at the moment

Section 2: Personal Care
- o I can look after myself normally without causing extra pain.
- o I can look after myself normally but it is very painful.
- o It is painful to look after myself and I am slow and careful.
- o I need some help but manage most of my personal care.
- o I need help every day in most aspects of self care.
- o I do not get dressed, I wash with difficulty and stay in bed.

Section 3: Lifting
- o I can lift heavy weights without extra pain.
- o I can lift heavy weights but it gives extra pain.
- o Pain prevents me from lifting heavy weights off the floor but I can manage if they are conveniently positioned for example on a table.
- o Pain prevents me from lifting heavy weights but I can manage light to medium weights if they are conveniently positioned.
- o I can lift only very light weights.
- o I cannot lift or carry anything at all.

Section 4: Walking
- o Pain does not prevent me walking any distance.
- o Pain prevents me walking more than 1 km.
- o Pain prevents me walking more than 0.5 km.
- o Pain prevents me walking more than 0.25 km.
- o I can only walk using a stick or crutches.
- o I am in bed most of the time and have to crawl to the toilet.

Section 5: Sitting
- o I can sit in any chair as long as I like.
- o I can only sit in my favourite chair as long as I like.
- o Pain prevents me sitting more than 1 hour.
- o Pain prevents me from sitting more than 30 minutes.
- o Pain prevents me from sitting more than 10 minutes.
- o Pain prevents me from sitting at all.

Section 6: Standing
- o I can stand as long as I want without extra pain.
- o I can stand as long as I want but it gives me extra pain.
- o Pain prevents me from standing for more than 1 hour.
- o Pain prevents me from standing for more than 30 minutes.
- o Pain prevents me from standing for more than 10 minutes.
- o Pain prevents me from standing at all.

Section 7: Sleeping
- o My sleep is never disturbed by pain.
- o My sleep is occasionally disturbed by pain.
- o Because of pain I have less than 6 hours sleep.
- o Because of pain I have less than 4 hours sleep.
- o Because of pain I have less than 2 hours of sleep.
- o Pain prevents me from sleeping at all.

Section 8: Sex Life
- o My sex life is normal and causes no extra pain.
- o My sex life is normal but causes some extra pain.
- o My sex life is nearly normal but is very painful.
- o My sex life is severely restricted by pain.
- o My sex life is nearly absent because of pain.
- o Pain prevents any sex life at all.
- o Question not relevant for my situation

Section 9: Social Life
- o My social life is normal and causes me no extra pain.
- o My social life is normal but increases the degree of pain.
- o Pain has no significant effect on my social life apart from limiting energetic interests eg sport.
- o Pain has restricted my social life and I do not go out as often.
- o Pain has restricted my social life to my home.
- o I have no social life because of pain.

Section 10: Travelling
- o I can travel anywhere without extra pain.
- o I can travel anywhere but it gives me extra pain.
- o Pain is bad but I manage journeys over 2 hours.
- o Pain restricts me to journeys of less than 1 hour.
- o Pain restricts me to short necessary journeys under 30 minutes.
- o Pain prevents me from traveling except to receive treatment.

Section 11: Satisfaction

If you had to spend the rest of your life with the symptoms you have right now, how would you feel about it?
- o Very satisfied
- o Somewhat satisfied
- o Neither satisfied nor dissatisfied
- o Somewhat dissatisfied
- o Very dissatisfied

Section 12: Medication

During the past week how often have you taken pain medication, including prescribed narcotics or over-the-counter medications, for your back or leg (sciatica) pain?
- o Not at all
- o Once a week
- o Once every couple of days
- o Once or twice a day
- o Three or more times a day

Section 13: Activity

For the following two questions please consider the **last 4 weeks** and use the number of days to respond.

a) During the past 4 weeks about how many days did you cut down on the things you usually do for more than half of the day because of back pain or leg pain (sciatica)?

__________N° of days

b) During the past 4 weeks about how many days did back pain or leg pain (sciatica) keep you from work or school?

__________N° of days

Section 14: Pain

a) Please mark on the scale below the level of your **low back pain today**.
0 = no pain, 10 = worst pain imaginable.

0 10

b) Please mark on the scale below the level of your **leg (sciatica) pain today**.
0 = no pain, 10 = worst pain imaginable.

0 10

Section15: Further comments
Do you have any further comments to explain your responses today?

____

____

____

____

Should this require further clarification the investigator may contact you directly.

APPENDIX VI.1

Automatic landmark identification with rasterstereographic assessment of thoracolumbar curvature: differences between back shape phantom, healthy volunteer and preoperative backs

Purpose: To provide a representation of the intra-session differences between the automatic landmark localisation derived through rasterstereography across 5 trials within a 5 minute session. Comparisons between the rasterstereographic profiles obtained for a thermoplastic back phantom, a healthy volunteer and a pre-operative lumbar surgery case, were compiled for dorsal and sagittal views. This was intended to reveal the potential for variation in rasterstereographic landmark identification within a short session. This exercise may also reflect the extent of lateral and anteroposterior (AP) postural sway in adults in vivo, however additional investigations were made to explore this physiological feature (Appendices VIII.1-3).

Background: A notable feature of assessing surface spinal curvature using video rasterstereography is the automatic landmark identification, which reduces the potential for human error in manually detecting key features (Drerup 1982; Drerup and Hierholzer 1987a). A shortcoming however is accepting possible machine error, despite the instrument allowing for repositioning of marked points. Video rasterstereography automatically identifies four anatomical landmarks for spinal curvature analysis: the vertebral prominens (VP), the left and right lumbosacral dimples (overlying the posterior superior iliac spines) and a sacral point (SP) representing the beginning of the rima ani (Drerup and Hierholzer 1987a; Drerup and Hierholzer 1987b). The intrinsic localisation accuracy of a single landmark has been reported as slightly more than 1mm for the first three landmarks, with the sacral point being more variable (Drerup and Hierholzer 1987a). The deviation of the landmark distance between the vertebral prominens and the mid-point of the dimples is reported to be 2.2mm in upright standing and 4.3mm when different pelvic tilts were imposed (Drerup and Hierholzer 1987a). The variability of landmark identification in the region of the lumbosacral spine was of relevance to the prospective arm of the primary investigation given the surgical cases were receiving intervention that had the potential to affect the lumbar curvature. Instrument-related methodological influences on the derivation of lumbar curvature as measured with rasterstereography were therefore of interest.

Hypotheses: It was hypothesised that there would be a subtle but significant difference in the intra-session caudal landmarks detected with rasterstereography. The sagittal rasterstereographic profiles in vivo would indicate variability in the AP plane. When compared to the profiles obtained for a thermoplastic spinal phantom, the variation noted in vivo would be greater.

Method: Baseline rasterstereographic images derived from: a thermoplastic spinal phantom (based on a teenage female with mild scoliosis), a healthy volunteer (38 year old female), and a preoperative lumbar surgery case (58 year old female) were compiled from the main study data archive. The five intra-session profiles for each of these were then scanned at a standardised 600dpi in gray scale and overlaid using Adobe Photoshop CS2 in order to afford a representation of the intra-session automatic landmark distribution. The VP was employed as the fixed reference point used to construct both the dorsal and sagittal intra-session profiles, with the zero-point on the y-axis (x-axis zero) overlaid as accurately as manually possible using the software. For the sagittal profile, the vertical distance between the vertebral prominens and the dimple midline (DM) was standardised to the baseline first trial length using the image-sizing tool. To provide a quantitative assessment of the variation in landmark position, measurements of the most visually apparent dispersed single landmark in the dorsal view per subject were made using electronic digital calipers. The distance between the most extreme landmark centre-points in the medial-lateral (ML) and superior-inferior (SI) dimensions was made and scaled according to the given rasterstereographic profile dimensions (Figure VI.1.1). Additionally, the distance between the most extreme lines indicating the mid-point of the dimples (mDM) was measured on the compiled profile per case at the level of the dimples.

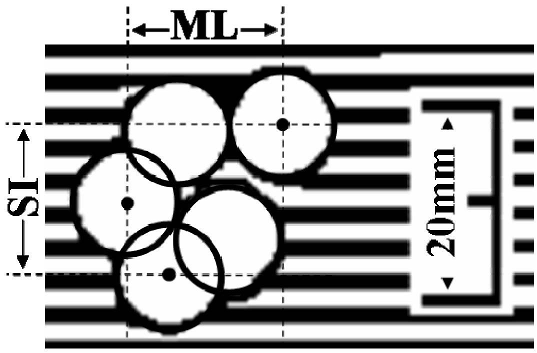


Figure VI.1.1: Measurement method used for quantifying the variation in the rasterstereography-derived landmark position in the medial-lateral (ML) and superior-inferior (SI) planes according to the scaling of the instrument. Distances between centres of the extreme points of the most variable distal landmark were measured with digital calipers based on visual inspection of the overlaid images.

Results: Compiled dorsal (Figure VI.1.2) and sagittal (Figure VI.1.3) profile images for the three cases are presented. As expected, variations in the landmarks in the region of the dorsal lumbosacral spine are most notable in the in vivo adults when compared to the back phantom example modeled on a younger female. Very minor variation in the back phantom was seen for the right dimple [ML 1.2mm; SI 1.0mm] while the mDM range was 1.2mm (Figure VI.1.2 A). Greater variation was seen in the profiles of the healthy volunteer, than for the pre-surgical case, particularly in the dorsal view. The widest ML distributed landmark for the healthy volunteer was the left dimple (ML 22.2mm) and the sacral point for the most widely SI-distributed landmark (SI 33.9mm). The mDM deviated by 16.0mm in the healthy volunteer. The widest ML and SI distributed landmark for the pre-surgical case was the SP (ML 10.2mm, SI 5.4mm), while their mDM deviation range was 7.1mm.

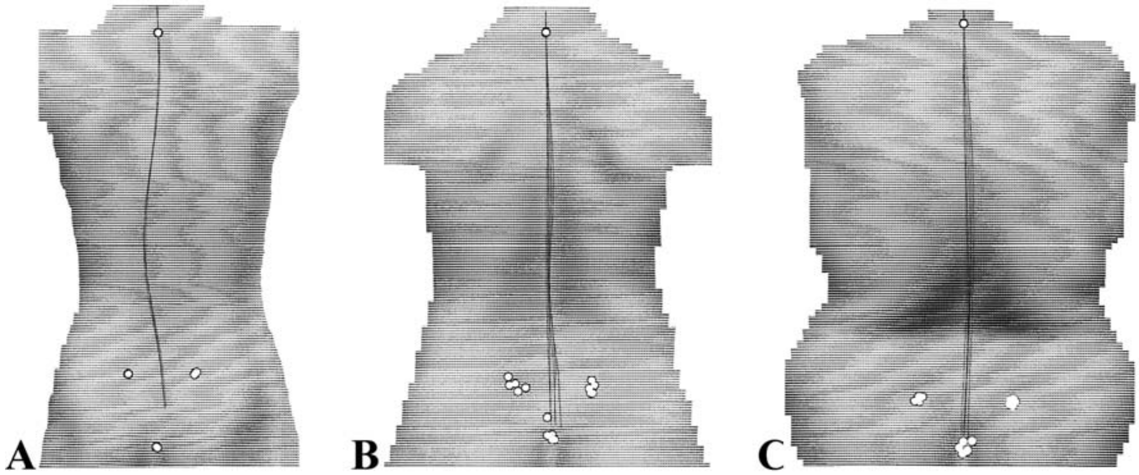


Figure VI.1.2: Compiled dorsal view images for: a thermoplastic spinal phantom [15yrs female] (A); healthy volunteer [38yrs female] (B); and a pre-operative lumbar surgery case [58yrs female] representing 5 intra-session overlaid images derived within a 5 minute period. Computed landmarks are indicated with white dots and the spinal midline with a continuous line.

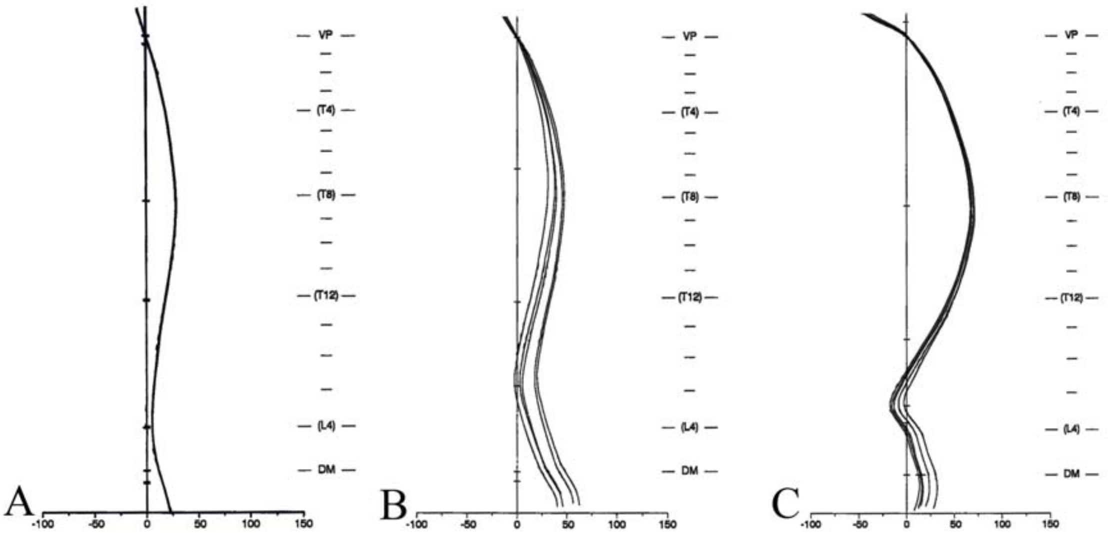


Figure VI.1.3: Compiled sagittal view profiles for: a thermoplastic spinal phantom [15yrs female] (A); healthy volunteer [38yrs female] (B); and a pre-operative lumbar surgery case [58yrs female] representing 5 intra-session overlaid images derived within a 5 minute period.

Discussion: The results of this study confirm the potential for variability in rasterstereographic automated landmark detection within a 5-minute session in vivo. This is not surprising given the human potential for postural sway both in the side-to-side and AP planes (Lord et al. 1991a). The very minor deviation of the right dimple of the spine of fixed curvature approximated (1.2mm) the 1mm accuracy reported for this measurement instrument (Drerup 1982; Drerup and Hierholzer 1987a). The dimple and sacral points in vivo were broadly precise and arguably more so in the surgical case. Potential explanation for this is discussed below.

The landmark precision in the two in vivo cases in this study showed deviation of their anatomical landmarks identified with rasterstereography in excess of that reported for the instrument. The VP landmark is reportedly identified with the best intrinsic precision, while the dimples and sacral point are increasingly less precise, respectively (Drerup 1982; Drerup and Hierholzer 1987a). The dorsal view of the pre-surgical case (Figure VI.1.2 [C]) and associated quantitative data for each landmark appear consistent with this finding. The fixed spine case revealed a minimally variable right dimple, with a precise SP. The healthy volunteer revealed the worst ML precision for the left dimple, and the worst SI precision for her SP landmark. The author speculates that the SI imprecision noted in the pre-surgical and healthy cases relates to the reported variability (2.2mm) of the intrinsic identification of the length between the VP and mid-DM points in standing (Drerup 1982; Drerup and Hierholzer 1987a). Stonelake et al (1988) reported trunk length derived from these two landmarks to be variable. The range of SI deviation for the SP in the in vivo cases in this study was greater by a multiple of 15 and 2.5 times the reported range in the healthy and surgical cases, respectively. Sacral dimples as visible from the skin surface have been shown to correspond to widely variable vertebral levels between cases (Stonelake et al. 1988). This normative anatomical variation may have contributed to the differences between detected landmarks via surface topography in the two cases studied here.

The sagittal profiles are clearly equivalent within the 5 trials for the back phantom curvature, but indicate movement in the AP plane for both the healthy and surgery cases. This is reasonable given that a known variability in trunk inclination relates to postural sway (refer to Appendices VIII.1-3). It is perhaps counterintuitive that the surgery case appeared less variable than the healthy volunteer considering the potential for back pain to increase postural sway (Hamaoui et al. 2004). The author speculates that the older aged pre-surgical case plus her lengthened thoracolumbar kyphosis, render her spine relatively hypomobile. Her acutely angled lumbosacral region may indicate a predominant motion point for postural sway AP compensation. It appears that the healthy volunteer employed a different strategy by varying her trunk inclination relatively en bloc for the entire thoracolumbar contour, although the minor differences in her lumbar profile are noted. Physiological strategies used in compensating during postural sway in quiet standing are the focus of the investigation described in Appendix VIII.3. Chapter 5 discusses normative data for surface spinal contour, outlining individual variability.

Part of the variability in landmark location between trials presented in this study may be due to the digital manipulation of each image, in order to apply appropriate scaling or sizing to accommodate the overlays. In addition, it is acknowledged that each Figure was produced from a set of profile printouts that were scanned (at a standardised dpi) to create digital images, whose variable quality may have impacted on the manipulation in Photoshop.

Based on the findings of this anecdotal study it is reasonable to accept that part of the variability in the identification of anatomical landmarks using rasterstereography may be a consequence of the variable human posture in standing or the user-interaction with the system. This may impact on other surface contour measures derived from this instrument.

Conclusions: The anatomical landmarks and resultant sagittal curvature derived through rasterstereography are both precise and accurate, as reported in the literature for a thermoplastic phantom spine of fixed shape. Variability exists in the automatic detection of the dimple and sacral landmarks in vivo for one healthy and one pre-operative case. This variation was in excess of expected values based on the literature. The potential for variation in landmark identification may influence the derivation of surface curvature, with a possible impact on both the healthy and surgical cases in the main investigation.

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APPENDIX VI.2

Intra-session and serial thoracolumbar surface curvature as determined with rasterstereography: comparisons between back shape phantom, healthy volunteer and preoperative lumbar surgery case

Purpose: To provide representation of intra-session and two year serial thoracolumbar curvature profiles, as derived using rasterstereography, for a thermoplastic back phantom, a healthy volunteer and a pre-operative lumbar surgery case. This study was intended as an extension of Appendix VI.1 to focus on detected thoracolumbar shape according to segmental kyphosis and lordosis as measured with rasterstereography. Of primary interest was the variability of derived sagittal curvature profiles within and between the three cases, and whether potential existed for rasterstereography to demonstrate real and meaningful change in localised lumbar lordosis from a bandwidth of normal diurnal and physiological variation; across the short and longer terms. Whether the surgical case demonstrated change that might be attributed to their decompressive surgery that was augmented with the Device for Intervertebral Motion (DIAM) interspinous implant(s), underpinned the considerations.

Background: The automatic landmark identification using rasterstereography has previously been described and studied (Appendix VI.1), the results of which indicate variability of lumbosacral landmark identification and trunk inclination for in vivo cases. An established disadvantage of the Cobb method of skeletal curvature assessment, discussed in the review by Vrtovec et al (2009), is its reference to tangents projected from the end-points of a region of interest, with little sensitivity to intraregional or segmental curvature (Vrtovec et al. 2009). Topographical methods for determining spinal shape from the surface, like rasterstereography, were developed in part as an advance on this limitation of assessments based on 2D plain radiographs and surface instruments that only reference curve end-points. Relative segmental curvature in relation to the kyphotic and lordotic shape in the sagittal plane is a parameter that can be derived from rasterstereography, perhaps extending its scope for reporting shape characteristics based on the back surface. Whether there was any intra-session or serial variability in segmental curvature (as detected by rasterstereography) within an individual in quiet standing, and to what degree any potential change might be evident, was of interest. This was relevant to the prospective arm of the primary investigation given the surgical cases were receiving an intervention that had the potential to reduce segmental lumbar lordosis by inducing a relative kyphosis at the index segment (Taylor et al. 2007). Evidence that supports the kyphosing effect of DIAM is limited (Phillips et al. 2006; Crawford et al. 2009a; Sobottke et al. 2009). The derivation of lumbar curvature as measured with rasterstereography were therefore of interest.

Hypotheses: It was hypothesised that there would be variability in the intra-session and serial thoracolumbar curvature profile for the in vivo cases as an effect of normal variation in standing posture. Variation in the serial profiles spanning two years would be greater than those derived from a single 5-minute session.

Method: Two sets of rasterstereographic images from: a thermoplastic spinal phantom (based on a teenage female), a healthy volunteer (58 year old female), and a preoperative lumbar surgery case (58 year old female) were compiled from the main study archive. The volunteer case was chosen for her equivalence (gender, age and stature) to the surgical case, who was selected as the individual who presented with the most flattening in regional lumbar lordosis between baseline and six weeks postoperatively (as determined from the published surgical series presented in Chapter 6) (Crawford et al. 2009a). This subject received decompressive surgery (laminotomy, microdiscectomy and formaminotomy) augmented with tri-level DIAMs, and as such represented an atypical and relatively extreme case.

Two sets of images per case involved: (1) Five intra-session baseline/preoperative curvature sagittal profiles; and (2) Five serial images representing the profiles obtained for baseline/preoperatively, six weeks, six months, one, and two year time-points/postoperatively. The second of the 5-trial images per time-point was used for each subject in the serial comparison. The procedure used to compile the composite images was the same as that described earlier for the sagittal profile of Appendix VI.1. The vertebral prominens (VP) was employed as the fixed reference point, with the zero-point on the y-axis (x-axis zero) overlaid and the vertical distance between the VP and the dimple midline (DM) standardised to the baseline first trial length. Colours were used to identify the profiles for different time-points in the serial image compilation. Quantitative assessment of the healthy and surgical subjects' serial curvature profiles involved measurement of the depth of the peak lordosis for each time-point, which for both cases occurred in the region of L3/4. This was achieved with electronic digital callipers and values were scaled according to the x-axis.

Results: Compiled intra-session (Figure VI.2.1) and serial (Figure VI.2.2) profile images for the three cases are presented. Figure VI.2.3 demonstrates the serial profiles for the surgical case that have been magnified to reveal the behaviour of the peak of the lumbar lordoses (L3/4) from which quantitative measurements were derived. As expected, variations in thoracolumbar surface curvature, determined through rasterstereography, are most notable in the in vivo adults when compared to the back phantom. Intra-session variability was minimal for the phantom and surgical case where differences were small. The largest horizontal difference at the L3/4 level between profiles for the healthy case was 8.21mm. The hypothesised greater variability for serial curvature as compared with that achieved within a 5-minute session was true for all 3 subjects. Against expectations, the serial profiles for the surgical and healthy cases indicated a flattening of the peak lumbar lordosis in the first 6 months postoperatively (or later), which appeared to return toward preoperative (or baseline) values thereafter.

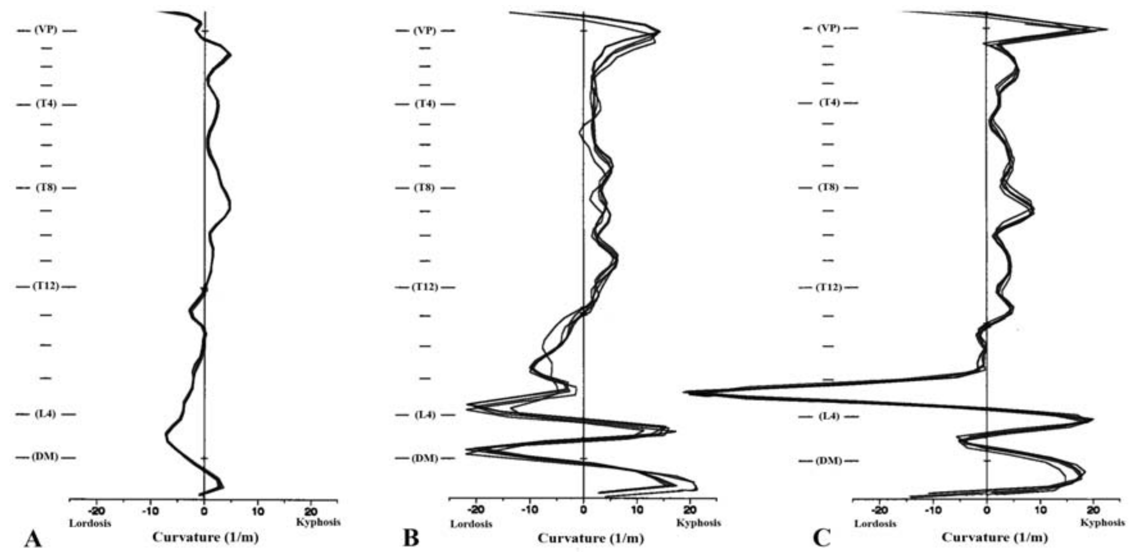

Figure VI.2.1: Schematic representation of the intra-session sagittal curvature profiles obtained via rasterstereography from: (A) Thermoplastic back phantom (based on a teenage girl diagnosed with mild scoliosis); (B) Healthy female (58yrs); and (C) Female patient who underwent lumbar decompressive surgery augmented with three DIAMs, one each at L2/3, L3/4 and L4/5. The y-axis represents the sequential vertebral levels between the vertebral prominens (VP) and the dimple midline (DM). The x-axis indicates the amount of lordosis or kyphosis curvature (1/m). Wider variation is demonstrated for the in vivo cases (B&C) compared to the back phantom (A) where lines are nearly identical.

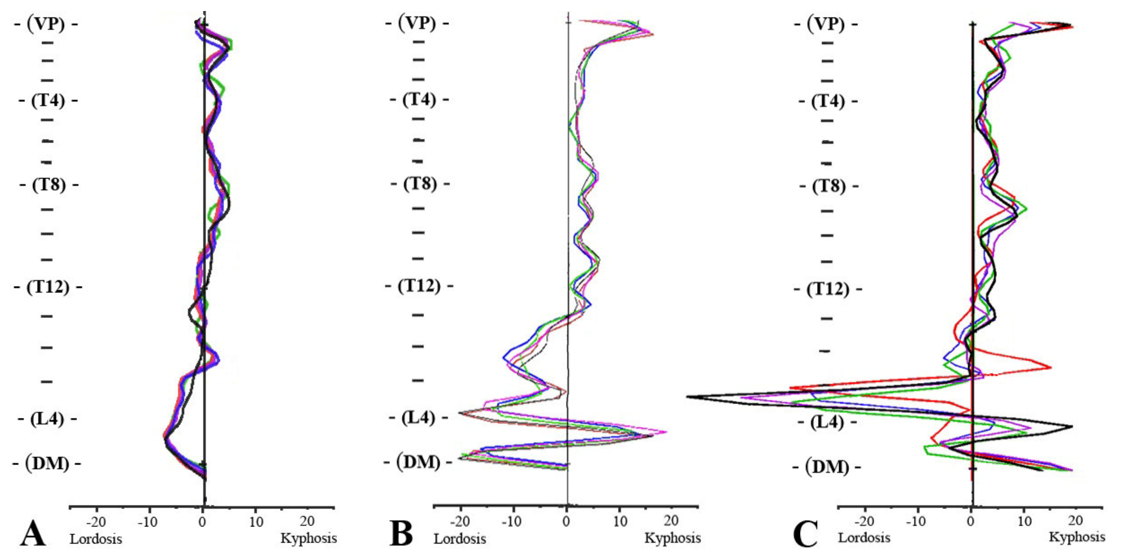

Figure VI.2.2: Schematic representation of the serial sagittal curvature profiles obtained via rasterstereography from: (A) Thermoplastic back phantom [based on a teenage girl diagnosed with mild scoliosis; (Goh et al. 1999a)]; (B) Healthy female (58yrs); and (C) Female patient who underwent lumbar decompressive surgery augmented with three DIAMs, one each at L2/3, L3/4 and L4/5. The y-axis represents the sequential vertebral levels between the vertebral prominens (VP) and the dimple midline (DM). The x-axis indicates the amount of lordosis or kyphosis curvature (l/m). Baseline/preoperative (black), 6 weeks (red), 6 months (blue), 1 year (green), and 2 years (purple) time-point profiles for each case are represented. The thermoplastic back phantom compilation (A) indicates a relatively 'flat' spine as depicted by only minor deviation into lordosis or kyphosis; the 6w, 6m and 24m profiles are very similar and as such the red, purple and blue lines are overlaid. Minimal variation for the healthy case (B) is noted within the two-year period. The profiles for the surgical case (C) approximated each other but for the region centred between L3-L4 where less lordosis is noted for each postoperative point in relation to the preoperative contour.

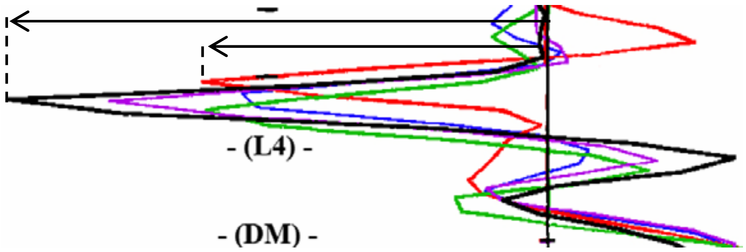

Figure VI.2.3: Magnified image of the serial curvature profiles for the surgical case, demonstrating the change in depth over 2 years of the lumbar lordosis. Depth measurements were made using a digital micrometer spanning from the y-axis to the peak of the lordotic curve, for each time-point indicated in different colours. Lordotic peaks of the baseline (black) and 6 week postoperative (red) profiles are indicated with arrows to depict the span used to measure their depth (in mm) in the horizontal plane.

Measurements determining the horizontal distance of the depth of the peak lordosis have been included in Table VI.2.1 and reveal a deeper (x 2.6) peak lordosis at baseline for the surgical (57.08mm) compared to the healthy (21.89mm) case. The surgical case had a reduced lordosis at the 6 week (postoperative; red profile) time-point (actual value; change compared to baseline) (36.74mm; -20.34) that reduced further by 6 months (32.03mm; -25.05; blue profile) but appeared to return to baseline values at 12 (36.20mm; -20.88) and 24 months (46.21mm; -10.87). The healthy volunteer also revealed a reduced lordosis at all time-points compared to baseline, with a peak reduction also at 6 months (-7.84mm); however this was less marked (reduced by 36% from their baseline value) than the surgical case (44% of baseline).

Table VII.2.1: Quantitative results for the lumbar lordosis depth (mm) at five time-points in a healthy and surgical case whose surface curvatures (assessed via rasterstereography) were followed over two years. The surgical case had received lumbar surgery augmented with a DIAM interspinous implant after their initial baseline thoracolumbar surface curvature images were profiled. Measurements were derived using digital callipers based on a compiled image created from printed rasterstereography profiles.

Two Year Serial Rasterstereography Curvature Profiles

	Healthy		**Surgical**	
mm	Actual	B Comparison	Actual	B Comparison
B	**21.89**		**57.08**	
6w	21.50	-0.39	36.74	-20.34
6m	14.05	**-7.84**	32.03	**-25.05**
12m	14.99	-6.9	36.20	-20.88
24m	19.92	-4.97	46.21	-10.87

B Comparison=difference between the follow-up time-point compared to baseline/preoperative values; Negative sign indicates a flattening of the lordosis

Discussion: As expected, the intra-session variability indicated in this study of thoracolumbar curvature was greater for the two in vivo subjects as compared with the back phantom. Interestingly, the variation seen within the same session for the healthy volunteer was again greater than that shown in the surgical case profiles, which had very similar overlaid profiles in the region of L3/4. The healthy case used in this study was different to the one compared earlier in Appendix VI.1, while the surgical profiles were from the same individual. This may lend support to the supposition presented in Appendix VI.1 that the surgical case was a woman whose thoracolumbar spinal mobility was limited. However, no range of movement assessment was performed to asses this and therefore the notion remains conjecture. Both in vivo cases presented here were the same age and of similar stature, so potential influences on spinal shape relating to age and gender were not necessarily applicable. It appears reasonable to speculate that the surgical case employed for these two appendices had multilevel lumbar degeneration given she was implanted with three DIAMs in treatment of her lumbar pathology. The latest stage of the lumbar degenerative cascade is known to result in reduced spinal mobility (Kirkaldy-Willis et al. 1978).

Figure VI.2.2 revealed a reduced lordosis in the region of L3/4 in the serial profiles for the healthy *and* surgical cases, both being most pronounced at six months later/postoperatively. This was against expectations where reduction of the peak lordosis, if any, was most likely to occur in the surgical case where implantation with the DIAM had the potential to induce a mild kyphosis (Taylor et al. 2007; Sobottke et al. 2009). Flattening of the regional lordosis at 6 weeks after DIAM-augmented surgery had been previously reported compared to healthy Normals where no change was demonstrated (Crawford et al. 2009a). Although the surgical case evidenced a greater reduction compared to baseline lordosis (44%) than the healthy case (36%), it is difficult to be conclusive as to whether this change represents anything other than methodological error or physiological normal variation. The influences of diurnal (or even seasonal) fluctuations in surface posture were not specifically assessed or accounted for methodologically and therefore their potential to alter the output for these two cases, whose baseline images were taken within 2 months of each other, requires acknowledgement. It might be anticipated that a change in body weight would alter the skin contour and therefore present variably when measured photogrammetrically. Even though patients were imaged in their underpants alone, wearing tight clothing immediately prior to assessment (for example) may have restricted the local tissues enough to effect change overlying the referenced posterior back surface. Assessing a series of subjects over a 12 hour phase might help to better appreciate the diurnal variation and rasterstereography's potential to measure it. Similarly, standardising the time of day for each assessment may mitigate any diurnal influence.

Further assessment of a broader series of both healthy and surgical cases would need to be undertaken in order to appreciate any differences in change to local curvature as assessed from the surface using rasterstereography in this way. Conclusions based on these two cases can therefore not be confidently made. The utility of this application of rasterstereographic analysis of curvature may represent a future direction in attempts to capture more local shape characteristics from the surface employing a non-ionising instrument.

The relative kyphosing effect of DIAM surgery has been shown to be isolated to the index segment in vivo, with only minimal flattening (<5˚) at the skeletal level, which returns to baseline after a year (Sobottke et al. 2009). It seemed unlikely that surface spinal curvature would also reflect this change given the correlation between surface and skeletal shape in the lumbar region is only fair (Appendix VIII.1) (Bryan et al. 1989; Bryant et al. 1989), which may in part be based on a deeper skin-spinous process-vertebral body distance (Appendices VIII.2&3). It is therefore somewhat encouraging that the serial curvature overlays used in the present investigation revealed a local change, despite its tenuous significance.

Rasterstereography derives measures of thoracolumbar curvature based on the behaviour of light projected on the skin surface (Drerup 1982). As a result, any feature of the skin surface that might make automatic identification of landmarks difficult has the potential to affect data derived from the instrument. Speculatively, the presence of scarring, tattoos, birthmarks and dense body hair could alter, or at least confuse, the derivation of data points based on light reflection from the back surface. Similarly as indicated previously, an individual whose weight fluctuates within the period of observation may have an altered fat distribution and associated skin folds, which have the potential to influence the contours of the skin surface. As examples, the early flattening of the lumbar contour that the surgical case presented with here, may have been a consequence of her having lost weight, scarring or muscle spasm/swelling local to the L3/4 region where the change in curvature was noted. It might be argued that the changes seen in both the adult women assessed in this study, related more to these normal biological variations of skin contour rather than system error or flattening as a consequence of lumbar surgery.

A proportion of the variability of curvature between trials presented in this study may be due to digital manipulation of each image in order to apply appropriate scaling or sizing to accommodate the overlays. In addition, it is acknowledged that each figure was produced from a set of profile printouts that were scanned to create digital images, whose variable quality may have impacted on their manipulation in Photoshop.

Conclusions based on the limited cases explored in this study should be considered cautiously in terms of their wider application. This investigation has explored an interesting feature of the rasterstereographic capabilities in assessing thoracolumbar curvature and presented a potential method for serial comparison of localised curvature in a postoperative cohort. Limitations on the use of rasterstereography in this cohort are outlined and relate to normal biological variation in surface contours. This study would need to be extended to assess a substantial cohort in this way to better appreciate the value of this use of the instrument.

Conclusions: Two adult women registered wider intra-session and serial change in their local lumbar curvature than a thermoplastic back phantom. Serial sagittal curvature profiles for a back phantom, healthy volunteer and a lumbar surgery case were more variable than those obtained within a session. Two in vivo female cases showed a serial flattening of the lordosis at the L3/4 level, which peaked at 6 months after baseline and reverted in the direction of baseline values out to two years.

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APPENDIX VII.1

Postural sway in healthy adult volunteers: a potential contributor to variability in surface spinal curvature assessment in standing

Purpose: To investigate postural sway for 11 healthy volunteers in standing with two arm positions: arms by the side and in the clavicle position. Variability of postural sway was measured in relation to the anterior-posterior and medial-lateral planes, plus reported in terms of total two-dimensional sway area. Postural sway was explored as a potential influence on surface lumbar spinal curvature and thoracolumbar sagittal alignment.

Background: Postural balance is a key requirement in efficient standing, wherein an individual will ideally maintain their centre of mass within a narrow range of sway in relation to their feet (Schwab et al. 2006). The concept of this 'conus of economy', which Schwab et al (2006) credit to the work of Professor J. Dubousset, relates to the body's ability to maintain balance in standing using minimal effort and without external support. Figure VII.1.1 schematically illustrates this concept.

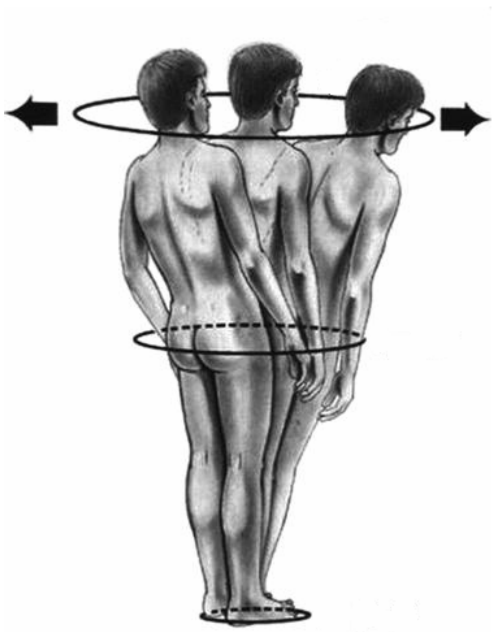

Figure VII.1.1: The concept of "Conus of Economy" (Schwab et al 2006). The body can sway within a conical-shaped region, centred at the feet, with minimal muscular effort. Extending the trunk beyond the economical cone may lead to imbalance and physical compensations. Image reproduced with permission and adapted from Schwab et al (2006 p. E960; retrieved on 29/12/09).

Spinal stability in erect stance is believed to be enhanced by the sagittal spinal curvatures developed with upright posture (Ferguson and Steffen 2003), which allow for an equilibrium that requires only phasic muscle activity to correct for sway (Ortengren and Andersson 1977; Duval-Beaupere et al. 1992). Movement of the trunk beyond acceptable limits may lead to energy-consuming spinal 'imbalance' and ultimately compensatory stepping, or a fall (Pearsall and Reid 1992; Schwab et al. 2006; Lafage et al. 2008).

Interest in postural sway relating to the spine generally centres on the quest for optimal skeletal alignment and its relationship to the line of gravity and associated physiological compensatory strategies. Some of the earliest studies of postural sway assessed balance in the elderly as an indicator of falls-risk, where a propensity to fall was reflected in increased sway in standing (Lord et al. 1991a,b). Extending the arms above the head elevates the centres of mass and volume within the trunk (Gagnon and Montpetit 1981; Duval-Beaupere and Robain 1987), which has the potential to result in an increased lever-arm that the body must then accommodate to maintain the cone of economy. Whether arm positions used in the main investigation had the potential to alter the measureable range of sway was of interest.

Various methods have been devised to assess postural sway ranging from simple mechanical devices such as the Sway-Meter (SM) (Lord et al. 1991a), to sophisticated laboratory-based systems involving photogrammetric motion analysis complemented with force-plate stabilometry technologies (e.g. VICON Motion System, OMGplc, Oxford, UK). As the importance of skeletal alignment in relation to the line of gravity is recognised in spinal surgery, the coordination of radiography with force-plate measurements appears to be gaining favour (Schwab et al. 2006). The SM was used for the purposes of this study of 11 healthy volunteers, with the VICON system used for two subjects to provide additional information (presented in Appendix VII.3).

Hypothesis: The range of postural sway for healthy adult volunteers assessed in standing would be unaffected by arm position.

Methods: This investigation involved the assessment of postural sway in standing for 11 healthy volunteers using the sway-meter (SM). The study tested differences in the range of sway during standing with two arm positions: arms by the side and in the clavicle position (previously reported in Chapter 2.3).

Postural sway in standing was assessed using a Sway-Meter (SM) system that was originally devised by Lord et al (1991) for the clinical screening of static standing balance in elderly populations. The SM consisted of a rigid 40cm pen-supporting rod that extended posteriorly from a belt worn securely around the waist at the level of the thoracolumbar spinal junction. The rod was positioned parallel to a height-adjustable surface on which a 120 g/m^2 white blank sheet of paper was placed. A felt-tipped pen with a tip diameter of 0.5 mm was secured at the end of the rod to allow for vertical displacement (although not measured), yet ensuring that the pen remained in contact with the paper during the duration of the test period.

Eleven volunteers (6F, 5M; mean 34.6 yrs) were assessed in two standing positions in an environment aimed at mimicking that employed for the rasterstereographic assessment of surface curvature in the main investigation (previously presented in Chapter 3.3). Both conditions required the subject to stand barefoot on a firm, short-pile carpeted surface, in a darkened room.

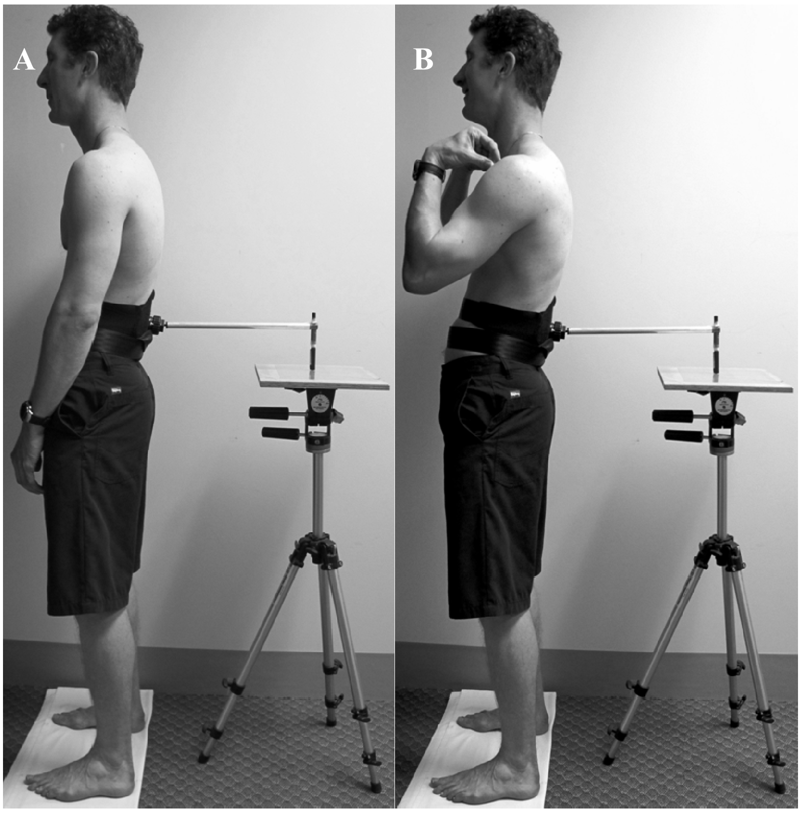

Figure VII.1.2: Sway-meter set-up employed in standing to assess the postural sway of a 23 yr old male healthy volunteer with his arms held comfortably by his side (A) and in the clavicle position (B). Volunteers stood barefoot on short-pile carpet in a darkened room with topographical gridlines projected on their back skin surface via rasterstereography. Subjects were asked to keep their eyes open during testing.

Subjects were not instructed as to how far their feet were to be apart, and instead were encouraged to assume a stance comfortable for them. The testing set-up has been illustrated in Figure VII.1.2. Topographical gridlines were projected on the subject’s dorsal surface from behind. Subjects were encouraged to keep their eyes open during the period of testing. Each subject was instructed to stand for a period of 5 minutes, each in two positions: arms relaxed by their side and in the ‘clavicle’ position previously described (refer to Chapter 2.3 & Appendix IV.2). The author tested all subjects using standardised instructions to describe the protocol. The first arm position was randomly selected and applied to minimise any possible order-of-testing effects, with the second arm position trial following the first when the arm position had been comfortably changed. Timing started when the subject had assumed the required arm position and the pen was placed on the recording paper to commence tracing the individual’s sway path. In order to identify any sway differences within the five-minute observation period, the pen was lightly lifted and repositioned on the underlying paper at one-minute intervals, thereby capturing 5 one-minute tracings. This was done to assess any possible inter-trial sway variation that may have occurred during the 5-trial rasterstereographic sessions.

Derived variables: The sway plots for each minute of the five-minute session per arm position were measured for their maximum excursion in the anterior-posterior (AP) and medial-lateral (ML) planes. Variability in the AP plane was of particular interest as a representation of the influence of sway on aspects of sagittal surface spinal curvature (e.g. trunk inclination). The most extreme anterior, posterior, left side and right side markings for each minute's tracings were identified and outlined using hand-drawn tangents that crossed to define a rectangular area. The distance between the anterior and posterior lines, and the left and right-side lines were measured (in mm) using an NSK MAX-CAL electronic digital calliper (Japan Micrometer MFG. CO., Ltd). The distance between the anterior and posterior lines were used to represent sway in the AP plane, while the distance between the left and right side lines represented sway in the ML plane. Total sway area was calculated as the product of these two variables. An example of the set of five 1-minute tracings achieved for one of the healthy subjects in both arm positions is presented in Figure VII.1.3.

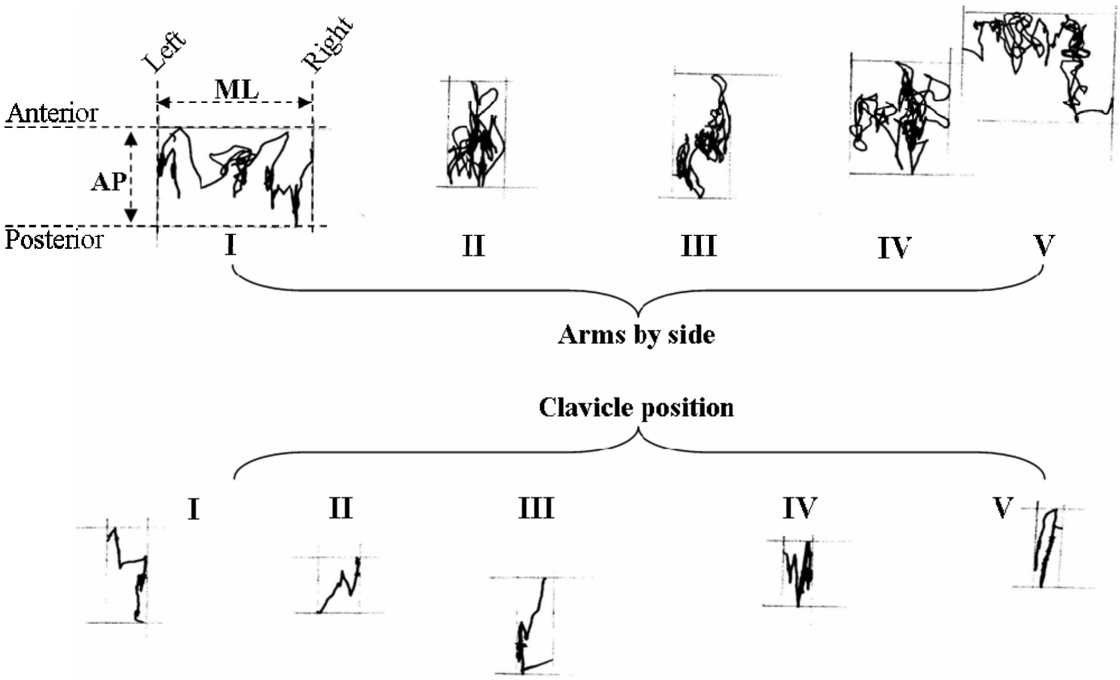

Figure VII.1.3: Sway-meter tracings from a 22 yr old healthy female volunteer derived in standing with her arms held comfortably by her side (top), plus with arms in the clavicle position (bottom). Each minute of the 5-minute trials are separately indicated (I-V). The extreme anterior, posterior, right and left-side markings have been identified and marked with four lines to define an area of sway (rectangle). The anteroposterior (AP) and medial-lateral (ML) parameters are outlined. All variables were recorded as a distance in millimetres. This patient reported feeling more stable in the clavicle position; her AP results (#1) are also detailed in Figure VII.1.4 (dotted line).

Descriptive statistics were employed for the individual intra-session data, with box-plots used to represent group results. Wilcoxon's signed rank tests were used to establish the significance of any differences in ML and AP excursion, and total sway area, between both arm positions. A probability of $p<0.05$ was used as the criterion to represent meaningful differences.

Results: Results for postural sway for 11 healthy volunteers as measured by the SM in standing with the arms by the side and in the clavicle position are shown in Table VII.1.1. Summarised group results are graphically presented in Figure VII.1.4. No significant differences were detected for any parameter between arm positions. Sway in the AP plane was greater that that in the ML plane for both arm positions ($p<0.05$).

Table VII.1.1: Postural sway distances [mm; mean (SD)] including medial-lateral (ML) and anteroposterior (AP) excursion and total enclosed area [mm^2; mean (SD)] as measured by the sway-meter, in 11 healthy volunteers who stood for five minutes each with their arms by their sides and in the clavicle position.

Cases		Side ML	Side AP	Side Area	Clavicle ML	Clavicle AP	Clavicle Area
1	22F	20.9 (9.8)	22.2 (1.8)	455.9 (195.2)	7.0 (1.5)	15.7 (3.8)	110.4 (39.4)
2	27F	25.7 (9.8)	13.1 (3.1)	324.8 (114.1)	29.9 (7.6)	15.5 (4.7)	437.6 (56.5)
3	38F	7.4 (3.6)	14.4 (4.3)	113.3 (72.3)	9.7 (4.3)	14.7 (4.9)	144.6 (85.8)
4	40F	3.3 (1.2)	11.2 (5.4)	36.5 (18.7)	3.4 (1.6)	6.9 (2.9)	24.6 (18.9)
5	58F	7.8 (2.4)	12.5 (5.6)	97.4 (48.1)	9.2 (5.9)	16.0 (8.3)	139.8 (85.3)
6	61F	10.8 (2.1)	26.9 (5.3)	296.4 (111.7)	7.4 (3.0)	30.7 (13.2)	237.2 (181.8)
7	22M	4.5 (1.6)	10.8 (1.7)	48.0 (13.2)	5.9 (2.8)	10.5 (5.9)	70.0 (65.6)
8	23M	7.6 (3.4)	23.6 (7.6)	172.3 (71.4)	9.3 (7.7)	23.0 (8.9)	209.4 (187.0)
9	24M	6.5 (2.8)	11.9 (3.5)	82.1 (50.4)	15.4 (11.4)	20.4 (8.6)	325.7 (256.9)
10	27M	6.0 (3.1)	12.7 (3.3)	75.6 (40.6)	3.3 (1.3)	7.7 (3.0)	27.8 (17.4)
11	39M	5.8 (1.9)	17.2 (5.9)	98.8 (48.7)	7.9 (4.1)	13.2 (2.3)	107.2 (67.1)
Group		**9.7 (7.1)**	**16.0 (5.6)**	**163.7 (135.7)**	**9.9 (7.4)**	**15.8 (6.9)**	**166.8 (127.4)**

Group row=mean (average SD for the 11 volunteers)

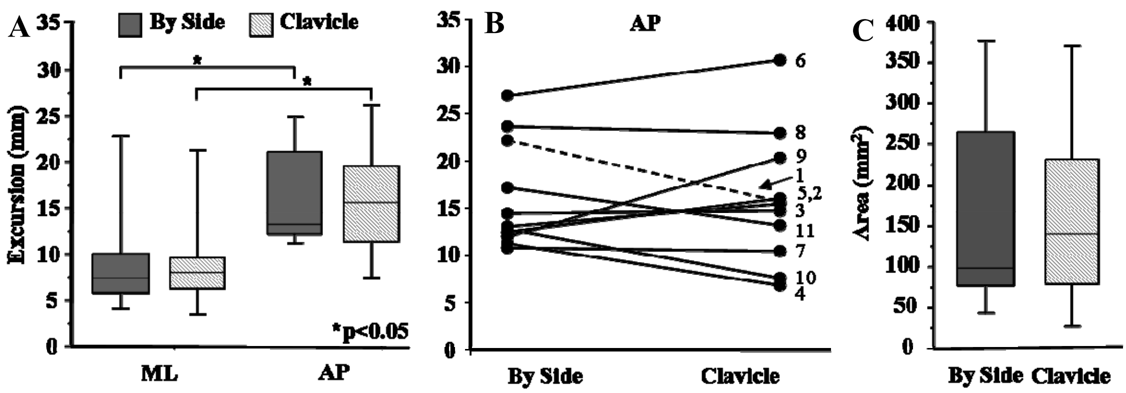

Figure VII.1.4: Graphical representation of group results for postural sway in standing in 11 healthy volunteers. Box-plots reveal the excursion (mm) in the medial-lateral (ML) and anteroposterior (AP) planes for standing in both arm positions (A). Individual results for excursion in the AP plane are illustrated (B). Box-plots for total sway area (mm^2) for both arm positions are outlined (C).

Discussion: The results of the present study demonstrate no effect of arm position on the maximum amplitude of postural sway in a group of healthy volunteers of a wide age range.

Inspection of Table VII.1.1 and Figure VII.1.4 reveal a somewhat variable data set for each measured variable, which may reflect the normal range of sway seen in healthy adults. Literature reports little if any gender difference in postural sway (Rogind et al. 2003; Schwab et al. 2006), so it is reasonable to apply the results of the present study as a group. However, a direct relationship with age has been previously established (Gill et al. 2001; Rogind et al. 2003), and may have impacted on the results. That said, sway increases significantly in the elderly compared to middle-age (Gill et al. 2001), and the oldest subjects involved in this investigation would generally only be considered middle-aged. Unfortunately the small sample used here makes intra-group age comparisons inappropriate.

Sway is known to increase, independent of age, with test difficulties such as vision deprivation and less stable foot support (Lord et al. 1991a; Gill et al. 2001; Rogind et al. 2003). Another aspect of this study that could have affected results is the darkened room and topographical gridline projection, which may have increased the difficulty of the test environment. Two (of 11) subjects verbally reported the topographical gridline projection to be off-putting, however did not perceive that it affected their ability to maintain standing. Given subjects were free to choose their own foot stance and were encouraged to keep their eyes open, it seems unlikely that the test environment provided any overt challenge to normal quiet standing.

Other biological influences on postural sway have been reported to include: back pain (Nies and Sinnott 1991; Mientjes and Frank 1999; Hamaoui et al. 2004; Smith et al. 2005); lumbar discectomy surgery (Bouche et al. 2006); and knee osteoarthritis (Hinman et al. 2002). One of the healthy volunteers of this study (#6) had previously undergone a total knee replacement for osteoarthritis; however she was asymptomatic at the time of testing and therefore stood as comfortably as she would normally. The higher energy required in maintaining the spinal imbalance of flat-back syndrome, is thought to result in fatigue and pain (Farcy and Schwab 1997; Glassman et al. 2005). The influences of lumbar pathologies on postural sway are relevant to the main investigation and are elaborated further in the main thesis discussion.

The present study showed AP excursion in standing to be greater than sway from side to side for both arm positions. Although the width of the lateral foot placement was not measured in this study, it is likely that it was comfortably broad since participants were able to elect their stance. This represented a comparable testing environment for the surgical group for the main investigation who were also asked to stand comfortably (in the clavicle position) without an imposed feet stance. This is different from the support provided by the feet in the AP plane, which is limited to the length of the feet, in contrast to the width of the distance of the ground between them. The impact of greater movement in the AP plane in relation to the main investigation is the influence that sway may have on sagittal spinal curvature; in particular those measures such as sagittal balance that reference the vertical. Unfortunately, it was not possible to concurrently measure surface spinal curvature via rasterstereography as well as postural sway using the SM due to the occluding position of the SM fixing strap and rod. Such an investigation may provide further detail for comparing the range of sway and curvature values. Additional study of potential physiological influences on spinal curvature is provided in Appendices VII.2 & VII.3.

Conclusions: The range of postural sway for 11 healthy adult volunteers assessed in standing was unaffected by arm position. Excursion in the AP plane was greater than that seen in the ML plane.

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APPENDIX VII.2

The influence of arm position on surface lumbar curvature assessed with rasterstereography in 10 healthy volunteers of a wide age range

Purpose: To investigate the effect of arm position on surface lumbar sagittal alignment as measured with video rasterstereography. This study had two primary intentions in exploring the influence of arm position on standing posture: to help explain variability seen in the sagittal alignment of healthy adults; and to contribute to accounting for limitations in the methodologies relating to patient arm position used by various radiographic sites in imaging the surgical cohort. Radiography clinics involved in the present study were provided with a standardised lateral radiography guideline however anecdotal patient discussions indicated the required positioning was not always applied. This study assessed the effect of standing using three different arm positions on surface sagittal alignment and lumbar lordosis as determined through rasterstereography. The three arm positions were: by the side, in the clavicle position, and elevated to 90˚ at the shoulders, elbows flexed.

Background: The position of the centre of gravity is known to change for an articulated body rather than being fixed as for a rigid structure. The centres of volume and gravity are higher when the arms are extended above the head as compared to a lower arm position (Gagnon and Montpetit 1981; Duval-Beaupere and Robain 1987). It seems theoretically possible that raising the arms into flexion may lead to a posterior shift of the centre of gravity to counterbalance the resultant anterior lever arm. Additionally, it also appears reasonable that arm position can influence how a standing person might adjust their range of postural sway to accommodate their ‘cone of economy’ (Schwab et al. 2006) (discussed earlier in Appendix VII.1). In suggesting optimum positioning for lateral radiography, Stagnara et al (1982) point to potential for arms held extended above the head to markedly alter kyphosis and lordosis of the spine, although their hypothesis was not substantiated with data (Stagnara 1982). A shift toward a negative sagittal vertical axis (SVA) was significant ($p<0.05$) in patients with spinal fusion when their arms were at 90˚ as compared with 30˚ forward elevation (Vedantam et al. 2000). However in the same patients, thoracic kyphosis, and regional and segmental lumbar lordosis were unaffected. Sagittal alignment and curvature in patients with back pain who had not had spinal fusion also remained unchanged between the two arm postures (Vedantam et al. 2000). Two studies from the same institution have reported that radiographic positions involving shoulder flexion, including the ‘clavicle’ position (Horton et al. 2005), result in negative shifts of the SVA, with the arms passively supported at 30˚, being superior in approximating comfortable standing (Marks et al. 2003; Marks et al. 2009). Another investigation from these authors found a negative shift in SVA in the clavicle position, which was less than with the arms held actively at 45˚ (Faro et al. 2004). Conversely, Horton et al (2005) found a small positive shift of the SVA in the clavicle position, subsequently recommending this position for superior visualisation of vertebral landmarks.

Whether any changes to sagittal alignment relating to arm position would be detected on the skin surface (calculated using the trunk length and inclination parameters derived from rasterstereography) was of interest. Similarly, changes to other sagittal curvature parameters including lumbar lordosis, thoracic kyphosis and pelvic incidence were assessed.

Hypothesis: In 11 healthy volunteers as assessed via rasterstereography, sagittal alignment (SVA) was expected to shift toward negativity with a move from arms by the side to the clavicle position, and then again with increased shoulder elevation at 90˚ during standing. In compensation for this, lumbar lordosis was expected to progressively increase with further arm elevation, with a reduction in pelvic incidence.

Methods: The surface spinal sagittal profiles for eleven healthy volunteers [6F, 5M; mean age 34.6yrs] were assessed in standing using three different arm positions: arms relaxed by the side, in the clavicle position (described previously in Chapter 3.7), and with the arms actively held at 90˚ shoulder flexion. In order to afford visibility of the axillae, which are necessary in identifying key anatomical landmarks using rasterstereography, the 90˚ position was assumed with the elbows positioned outside the line of the shoulder when viewed from behind (Figure VII.2.1). All three positions were explained to subjects prior to testing, and they were all familiar with the testing environment employed for rasterstereography. For testing, subjects stood barefoot on firm-pile carpet, in a darkened room, in their underwear. Subjects were directed to randomly select their order of arm positions, which they subsequently assumed, and when they indicated they were ready, a single rasterstereographic image was taken. Output from rasterstereographic assessment of surface curvature has been previously illustrated in Figure 3.3.

Derived data were recorded including: lumbar lordosis (LL), thoracic kyphosis (TK), pelvic incidence (PI) and global sagittal balance (GSB) for the three arm positions. GSB was calculated from the trunk length and inclination values via the tangent trigonometric function to derive a distance (mm) in the horizontal plane. The sagittal rasterstereographic variables employed in this investigation are represented in Figure VII.2.2. Data were reported using descriptive statistics and presented using box-plots. Comparisons between positions were assessed via Wilcoxon's signed rank tests. A $p<0.05$ was used to represent meaningful differences.

Results: Data for lumbar lordosis (LL), global sagittal balance (GSB), thoracic kyphosis (TK) and pelvic incidence (PI) obtained via rasterstereography in standing in each of the three arm positions including: arms by the side (side), the clavicle position (clavicle) and 90º active arm elevation, are presented via box-plots in Figure VII.2.3. Table VII.2.1 presents the data (mean (SD) [SEM]) for all measured variables.

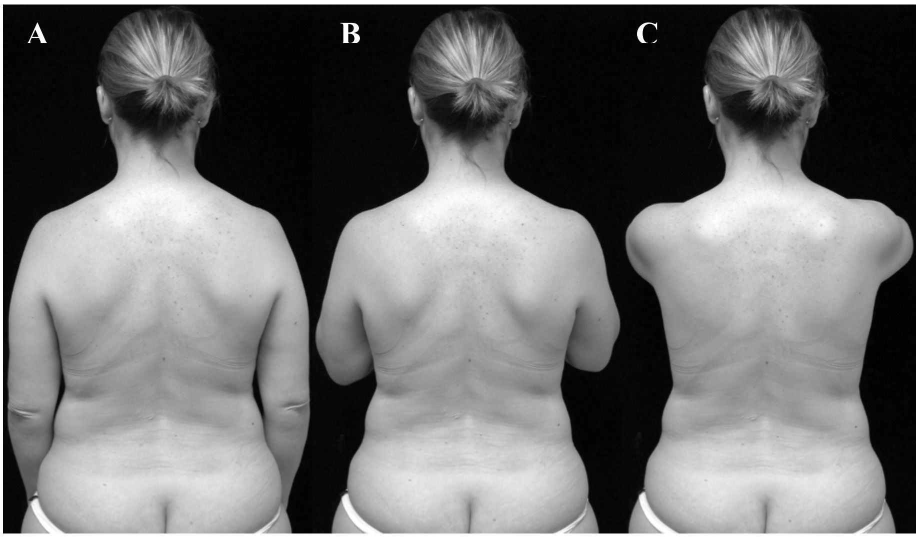

Figure VII.2.1: Images of a 40yr old female demonstrating the three arm positions used in standing for this study: arms by the side (A), clavicle (B) and 90˚ arm elevation (C).

The results of non-parametric paired comparisons indicate: significant increases in lumbar lordosis with the arms in 90˚ elevation as compared with the arms held by the side, and the clavicle position; a shift toward negative sagittal balance with increasing arm elevation; no detectable change in thoracic kyphosis; and reduced pelvic incidence at 90˚ compared with both other arm positions.

Table VII.2.1: Results (mean (SD) [SEM]) for lumbar lordosis, global sagittal balance, thoracic kyphosis and pelvic incidence as derived from rasterstereographic measurement of surface spinal curvature in 10 healthy volunteers standing in three arms positions: arms by the side, clavicle and 90˚ arm elevation.

	Arm Positions		
	By Side	Clavicle	90˚ Elevation
Lumbar Lordosis (º)	46.3 (10.5) [3.3]	47.8 (11.2) [3.5]	49.9 (10.9) [3.5]
Sagittal Balance (mm)	22.2 (21.9) [6.9]	7.7 (26.4) [8.3]	-18.1 (38.2) [12.1]
Thoracic Kyphosis (º)	58.1 (16.6) [5.2]	58.9 (21.1) [7.0]	57.8 (16.8) [5.6]
Pelvic Incidence (º)	22.4 (6.1) [1.9]	22.7 (6.2) [1.9]	20.4 (6.8) [2.2]

Discussion: In agreement with other studies discussing the effect of arm position on sagittal alignment (Vedantam et al. 2000; Marks et al. 2003; Faro et al. 2004; Marks et al. 2009), the results of the present study revealed a significant shift toward negative SVA with increasing arm elevation. In addition, this study also showed significantly increased lumbar lordosis and significantly decreased pelvic incidence at 90˚ shoulder elevation compared to the clavicle and relaxed standing postures, yet no detectable difference was noted between the clavicle and arms by the side positions for either variable.

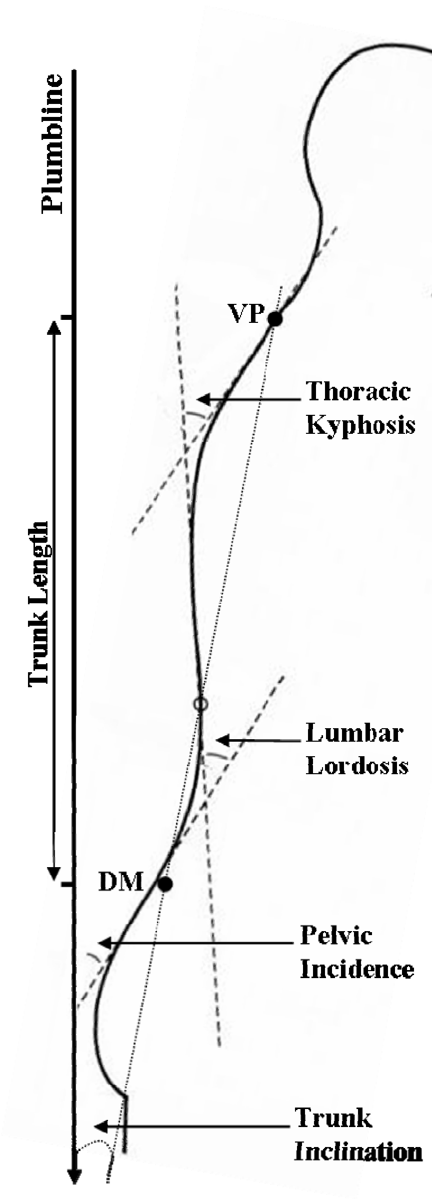

Figure VII.2.2: Schematic representation of the variables derived from rasterstereography in assessing spinal curvature from the skin surface in erect standing. Sagittal balance (in mm) was calculated with the tangent equation using the trunk inclination and length parameters. VP=vertebral prominens; DM=dimple midline. Forward lean of the subject is exaggerated. (Adapted from (Lippold et al. 2006).

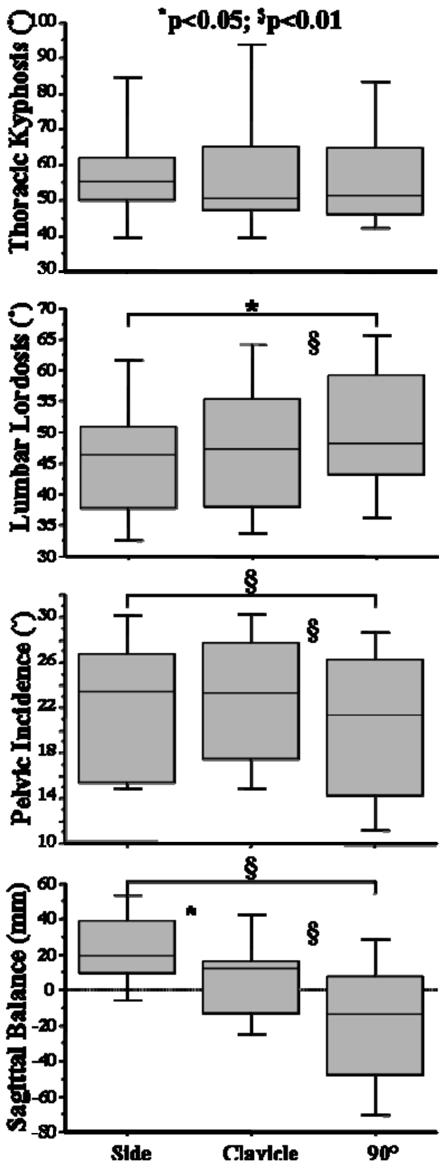

Figure VII.2.3: Box-plots for sagittal surface curvature variables in three arm positions in standing as determined via rasterstereography for 10 healthy asymptomatic volunteers

While Vedantam et al (2000) speculated that the negative shift in SVA they noted with arm elevation, related to compensations in the lower extremities rather than adjustments to spinal alignment where no skeletal parameter changed, the results of this study suggest spinal curvature alteration when the arms are elevated. The difference that surface assessment employed by this study might represent when compared to those employing radiography, and therefore skeletal measures, is acknowledged. This aspect is further explored in Appendices VIII.1-2. The results of the present study appear reasonable when an increased lumbar lordosis might be expected to compensate for a posterior shift of the trunk, as would be seen in a negative shift of the SVA. Similarly, to adjust for the likely higher centre of mass and the more posterior SVA, the hips and/or pelvis might be expected to posteriorly rotate to approximate the line of gravity. These two study findings, an increasing lumbar lordosis associated with a decreasing pelvic incidence, appear somewhat counterintuitive when an increased depth of lumbar lordosis is associated with an anteriorly rotated pelvis (Day et al. 1984). This aspect will be considered further in relation to the main thesis investigation (Chapter 5).

The primary investigation for this thesis used rasterstereography to measure surface assessment in a cohort of healthy volunteers for comparison to a group of lumbar surgery cases. The arm position used for the healthy subjects was that assumed comfortably, involving their arms positioned by their sides. The arm position employed for surface curvature measurement of the surgical cases was chosen to best compare with that used in skeletal radiographic assessment, and as such, the clavicle position was used. In light of the results of this small collateral study, where a significant negative shift in sagittal balance was noted for the clavicle position compared to the arms being held by the side, the values obtained for surface sagittal balance should only be compared between the two groups, with this difference and methodological limitation in mind.

The median values for sagittal balance in this cohort of ten healthy volunteers, lay within 20mm either side of neutral (zero) at each of the three standing positions. In addition to this variable becoming more negative with arm elevation, closer inspection of Figure VII.2.3 indicates increased variability within the group when the arms are elevated to 90˚. It might be speculated that this relates to an increased range of postural sway. This issue is addressed in Appendix VII.1.

Of primary relevance to interpretation of the skeletal radiographic results of the surgical cohort in the main investigation, is the significant differences noted in this study between the clavicle and 90˚ arm positions. If the standardised guidelines to use the clavicle position in patient positioning were not adhered to, it was probable that the radiographer elected to use a 90˚ elevated arm position instead given visibility of the lumbar spine was necessary. This study showed differences in surface lumbar lordosis, sagittal balance and pelvic incidence between the clavicle and 90˚ arm positions, and as such potential to affect the skeletal curvature can be assumed.

Conclusions: Increased lumbar lordosis occurred when the arms were at 90˚ elevation as compared with them being held by the side or in the clavicle position. A shift toward negative sagittal balance with increasing arm elevation was detected. Pelvic incidence reduced at the 90˚ shoulder elevation when compared with the other two arm positions. No change in thoracic kyphosis was noted between arm positions.

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APPENDIX VII.3

Postural sway in two healthy adult volunteers: ankle versus multi-joint compensatory strategy for quiet standing

Purpose: This study aimed to assess the potential for independent sagittal motion of body segments during standing, particularly within and close to the spine, as an adjunct to the exploration of postural sway in healthy volunteers. The concepts of single-joint ankle strategy versus multi-joint compensation for postural sway during quiet standing, represent controversial areas of biological analysis for which debate is high (Winter et al. 2001; Schieppati et al. 2002; Bottaro et al. 2005; Krishnamoorthy et al. 2005). This study sought to identify whether spine levels had the capacity for variable excursion in the AP plane during standing in the clavicle position.

Background: Upright stance is afforded by keeping the body's centre of gravity vertically above the base of support, which comprises the area of the feet and the ground between them. Standing balance is a complex function where individuals are known to use neuromuscular processes to maintain their position via physiological sway (Stelmach et al. 1989; Bottaro et al. 2005). Peripheral sensation, vision and vestibular sense are centrally integrated inputs that contribute to economically maintaining stability during stance (Lord et al. 1991a). Changes in the position of various joints along the kinetic chain are said to accompany postural sway in quiet standing (Hodges et al. 2002; Krishnamoorthy et al. 2005). The phenomenon of postural sway has been discussed earlier (Appendices VII.1 & VII.2).

A single-segment inverted pendulum model has been used to explain ankle-centred standing control, which assumes motion at other joints do not contribute independently to standing balance (Winter et al. 1998; Morasso and Schieppati 1999; Winter et al. 2001). Instead, the model hypothesises that quiet standing is stabilised primarily by active ankle joint mobility in combination with associated passive connective tissue elements (Winter et al. 1998). Perhaps in support of this model, Pinter et al (2008) have shown that the upper leg and head-arms-trunk (HAT) segments move in the same direction as the lower leg but with greater amplitude. In applying the inverted pendulum model, it appears reasonable that in standing, motion in the AP plane would increase from the ankle towards the shoulders. Effectively, the amplitude of movement at segments remote to the base of support is increased the further away from the ankle they are, yet coordinated as a dependent function of ankle control. This hypothesised ankle-strategy has been the basis for early postural control models (Winter et al. 1998; Morasso and Schieppati 1999; Winter et al. 2001).

More recently, the ankle-strategy model has been criticised for oversimplifying the complex sensorimotor control of the multisegmented human body in standing (Schieppati et al. 2002; Krishnamoorthy et al. 2005; Hsu et al. 2007; Kiemel et al. 2008; Pinter et al. 2008).

Contributions from the knee and hip joints in response to perturbed standing are recognised, with contraction of the lower limb, trunk and neck muscles being necessary physiological strategies employed to maintain balance of the centre of mass. Controversy regarding neuromuscular control in standing relate to involvement of multiple joints as coordinated yet different control centres. Pinter et al (2008) showed countermovement of the HAT relative to ankle joint angle and as an alternative to the inverted pendulum model, suggest that multi-joint control of unperturbed standing is more plausible. In their study assessing the coordination of major joints along the longitudinal axis in standing, Hsu et al (2007) concluded that control strategies involved coordinated multi-joint actions along the kinetic chain. Similarly, subtle leg and trunk movements are known to compensate for the minor balance perturbations associated with breathing while standing (Hodges et al. 2002), particularly in those with back pain (Hamaoui et al. 2004; Smith et al. 2005). Recent investigations therefore indicate that standing stability depends on multisegmental body movement that cannot be reduced to single joint neuromuscular control (Hodges et al. 2002; Krishnamoorthy et al. 2005; Hsu et al. 2007; Kiemel et al. 2008; Pinter et al. 2008).

Of relevance to the primary investigation of this thesis was the potential for segmental motion along the longitudinal axis in standing. An assumption was made that separate joint motion could affect sagittal thoracolumbar spinal curvature. Movement of the anatomical landmarks in the lumbosacral region were of particular interest. The study aimed to test whether the ankle or multi-joint strategy occurred with reference to the AP plane. If the inverted pendulum model were true, it was expected that AP excursion would increase serially with an increased distance of the anatomical landmark away from the floor (cephalad markers revealing greatest motion in the AP plane). It was anticipated that the legs and trunk would therefore move en bloc with the ankle essentially acting as a pivot point. Conversely, if the various landmarks move independent of their serial position in relation to the floor, a multi-joint control model may be more feasible.

Hypothesis: AP excursion during postural sway in standing would reveal spinal landmark excursion consistent with a multi-joint control strategy.

Methods: Movement of various anatomical landmarks as a function of postural sway in the standing 'clavicle' position was assessed for two subjects: a 39 year old female (height 158cm) and a 34 year old male (height 173cm). Data were collected using a 7-camera VICON MX motion analysis system (Oxford Metrics, UK). The cameras were tripod-mounted and positioned to surround the subject. Spherical (16 mm diameter) retro-reflective markers were manually placed and adhered by the author to the subject's skin surface using double-sided tape to overlie nine anatomical reference points. The 9 anatomical landmarks included the: C7, T4, T9, L1 and S2 spinous processes, bilateral greater trochanters (GT), and bilateral fibula heads (FH). The clavicle position and anatomical landmark placement for this analysis are indicated in Figure VII.3.1. Data were sampled at 60Hz and simultaneous input from all cameras was automatically converted into three-dimensional coordinates using VICON software. The VICON system references the centre of each marker, deriving motion data for each landmark in the X (anteroposterior; AP), Y (medial-lateral; ML) and Z (vertical) planes. For the purposes of this investigation, which aimed to assess motion in the sagittal plane only, the AP data was used for further analysis. Each subject stood barefoot on the short-pile carpeted floor of a large dimly lit motion-testing gymnasium. Subjects were asked to stand for a period of 5 minutes in the clavicle position and were encouraged to keep their eyes open. Motion analysis was recorded for the first 15 seconds of each minute for a total of five minutes with the subject standing comfortably in the clavicle position with their eyes open. Within the period of testing, specific timing of the data-capture was not known to the subject.

Derived variable: The X-plane data were selected to best represent AP excursion of the anatomical landmarks. Data was captured for the first 15 seconds of each minute, during the course of the 5 minutes. AP excursion was calculated as the distance (mm) reflected by the most extreme (maximum and minimum) values during each 15 second period. It was acknowledged that the 15 seconds of data collected per minute may not adequately report the true amplitude over the full 5 minutes, however the captured data was considered to be a reflection of each subject's capacity for AP motion during this period of observation. The AP ranges for each of the 9 landmarks were assessed in order to establish relative movement of the components of the lower body and torso. Line charts were employed to visually compare the results between and within each subject.

Results: The results for AP excursion of various body landmarks for a 39 year old female (158cm tall) and 34 year old male (173cm tall) are presented in Figure VII.3.1. The smallest range of AP excursion per landmark occurred at the fibula heads for both subjects. The second smallest excursion was recorded at the greater trochanters. The greatest AP motion was noted at the T4 landmark for the female and the L1 landmark for the male. A progressive increase in AP excursion occurred in the following order for each subject: Female: FH, GT, S2, C7, T9, L1, T4; Male: FH, GT, C7, T4, S2, T9, L1. Inter-landmark excursion ranged between 4.3mm and 23.7mm in the female, and between 3.6mm and 14.7mm in the male.

Discussion: The results of the present study lend support for the multi-joint strategy of postural sway in standing than for the arguably simpler ankle strategy, given the range of AP excursion did not increase serially away from the floor. Although the fibular head and greater trochanter landmarks followed expectations informed by the concept of an inverted pendulum, the spinal landmarks in these two healthy cases appear to behave somewhat independently. This may be an example of minor compensatory joint adjustments thought necessary in maintaining the multisegmented human balanced during upright stance (Hodges et al. 2002; Krishnamoorthy et al. 2005; Kiemel et al. 2008).

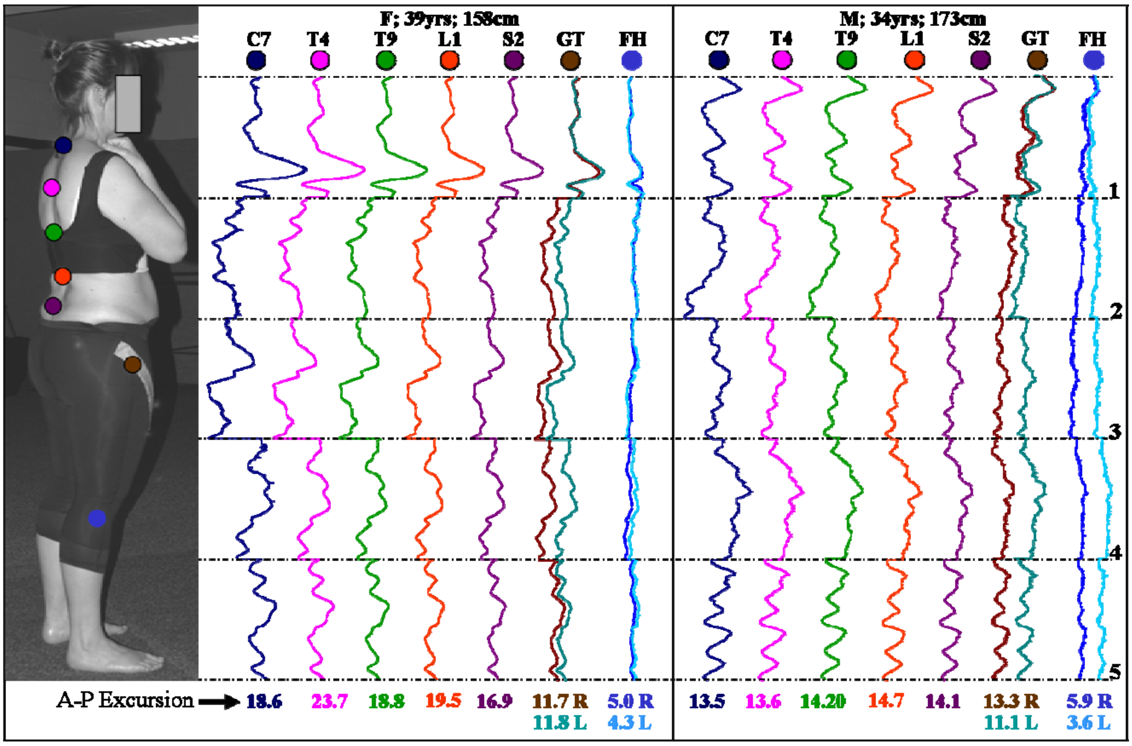

Figure VII.3.1: The results for postural sway of female and male healthy volunteers, who stood barefoot in the clavicle position for 5 minutes, are plotted on the x-axis to provide an indication of the amplitude of their AP motion. AP excursion was recorded for the first 15 seconds of each minute of the five minute test period. Separate landmarks data (colour-coded circles) have been presented as continuous coloured lines, with each minute of time separated along the y-axis (numbered dotted lines) and left and right greater trochanters (GT) and fibula head (FH) data overlaid. Maximum and minimum values recorded for each landmark were used to calculate a range of AP excursion, recorded as a distance in millimetres and presented in the bottom row. C7, T4, T9, L1 and S2 represent the landmark identified by the spinous process of the associated vertebra.

The literature used to provide background and context for this aspect of the study do not report motion for as many spinal landmarks as used in this small trial. As such, the intra-spinal motion noted here is not directly supported by previous findings. Inspection of the results of Hodges et al (2002; Figs. 5&7) reveal different profiles for angular motion and amplitude in standing between the neck, chest wall (T7), hip and knee, also assessed via VICON motion analysis. The Hodges et al landmarks align with the C7, T4/T9, GT and FH markers used in the present study, respectively. Similar to the present study, Hodges et al did not reveal a serial pattern of motion along the longitudinal axis, either between or within subjects. Their study emphasised the influence of breathing in postural stability, reporting a general motion of body segments during respiratory effort. However, they noted an absence of a fixed kinematic pattern in compensating for the postural disturbances secondary to breathing, noting angular motion of the trunk and lower limbs to be less than 1° (Hodges et al. 2002). Multi-segmental joint motion during postural sway is clearly influenced by respiratory effort, and varies between individuals (Hodges et al. 2002). Results of two cases assessed in the present study potentially reflect this; however a more extensive series would be required to verify trends.

The relevance of the small variation in AP motion noted in this trial between the spinal landmarks is questionable and only reflects differences in amplitude of 6.8mm in the female and 1.2mm in the male. Whether these subtle differences indicate a potential for sagittal spinal curvature to be appreciably altered during postural sway cannot be effectively deduced from this limited data set. Intuitively it seems unlikely that <7mm intra-spinal AP motion would result in any measureable change to the curvature of the lumbar region, for example, as derived from the skin surface. Using fixed intraosseous wire pins inserted into the spinous processes in 4 subjects, Steffen et al (1997) reported intersegmental motion at L3/4 to coincide with respiration. Although their study further highlights the influence of breathing on intersegmental lumbar motion, the likelihood for normal effort during quiet breathing in standing to appreciably alter lumbar angulation of measureable clinical significance is questionable (Steffen et al. 1997).

This study revealed similarities in AP excursion for the hip (GT) and knee (FH) landmarks for both subjects, yet there appeared to be more amplitude in spinal markers of the female subject. Postural sway is reportedly not influenced by gender (Hageman et al. 1995; Rogind et al. 2003). Kollegger et al (1992) assessed gender and age-related differences in postural sway between 30 healthy adults, and although they noted no difference between male and female cases aged <35yrs, men showed more sway than women in older age. This was most notable for AP excursion where women did not change with age, while the amplitude increased in older men. The AP motions of the two cases used in the present study, do not conform to these findings, and perhaps instead indicate an acceptable range of normal variation between individuals of a similar range. Rogind et al (2003) reported that increased body weight reduced ankle sway, while hypermobility and limited alcohol consumption were related to increased sway. These aspects were not tested in these two cases however their potential influence is noted.

Although the present two cases appear to indicate similar yet subtly independent segmental motion of the spine during standing in the clavicle position, it is not known whether these potential compensations are generated actively or passively. This issue is not fundamental to the main investigation; however the potential for pain to alter actively derived movement, suggests a possible influence on postural sway in those with back pain.

Conclusions: Intra-spinal variation in AP excursion during standing in the clavicle position was noted for two healthy adults. A serial increase in AP amplitude was only noted in the knee and hip landmarks but not in additional progressively more distant markers. This may lend support for a multi-joint compensatory mechanism in maintaining upright stance, over a single ankle strategy.

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APPENDIX VIII.1

The association between surface (rasterstereographic) and skeletal (radiographic) lumbar curvature: a series assessing 69 adult women

Purpose: An investigation was undertaken to establish the relationship between lumbar lordosis and sagittal alignment as measured via the skin surface using rasterstereography, and skeletally, employing erect plain radiography. Both surface and skeletal lumbar curvature were serially assessed in the prospective surgical cohort for the main study, with fewer x-rays used in order to limit unnecessary exposure to ionising radiation. Whether surface lumbar curvature in these patients was a reasonable surrogate for their skeletal measurements was of interest. As such, a comparison between skeletal and surface lumbar lordosis and alignment was assessed using an existing case series that had been investigated for spinal curvature in the thoracic region (Tan 2005).

Background: Non-invasive techniques have been developed to evaluate spinal posture from the skin surface, however these measures do not necessarily relate directly to the underlying skeletal arrangement (Bryant et al. 1989). Comparison of surface and skeletal kyphosis in the thoracic region has revealed a moderate to high correlation (r=0.70 (Goh et al. 2000); r=0.78 (Weiss and Elobeidi 2008); r=0.90 (Willner 1981)), with surface curvature underestimating that derived from skeletal radiographic imaging (Willner 1981; Goh et al. 2000; Weiss and Elobeidi 2008). A moderate relationship (r=0.65) was identified between surface and vertebral lordosis in the cervical spine (C2-7), which also showed that the surface curve underestimated the bony anatomy (Refshauge et al. 1994). Surface and skeletal lumbar lordosis comparisons have established both a poor (r=0.30) (Bryan et al. 1989) and high (r=0.80) (Willner 1981) correlation when flexirule and pantograph surface measures were compared, respectively, with skeletal measures derived from radiographs. The conflicting results of the lumbar region investigations may be due to different study populations and methods, with the discrepancy suggesting an inconclusive relationship between surface and skeletal lumbar contours. Prediction models have been developed based on the assumption that distances between the skin profile and the skeletal spinal curve are different and vary with spinal level and posture (Willner 1981; Bryant et al. 1989; Sicard and Gagnon 1993).

Variable spinous process length and the depth of overlying soft tissues are two primary factors said to contribute to observed differences between surface and skeletal contour (Refshauge et al. 1994; Goh et al. 2000; Weiss and Elobeidi 2008; Crawford et al. 2009a). When considering inter-regional differences in the relationship between skin and surface curvature, it is possible that the relationship in the thoracic spine would be stronger than that found in the lumbar region. Skin more closely approximates the spinous processes in the thoracic region where bony elements predominate, while more extensive myofascia overlies the vertebra in the lordotic lumbar region. Spinous processes of the middle thoracic vertebra are typically more caudally oriented, while those in the lumbar region typically have a broader prominence and are generally more horizontal (Figure VIII.1.1). This may contribute to differences in curvature when measured via surface and skeletal methods. Intra-regional variations between spinous process depths in the lumbar spine have been further explored in Appendix VIII.2.

To the knowledge of the author, no previous investigation has compared sagittal balance derived from trunk dimensions as measured from the body surface via rasterstereography, with lumbar regional sagittal balance. This study will explore the potential for this comparison.

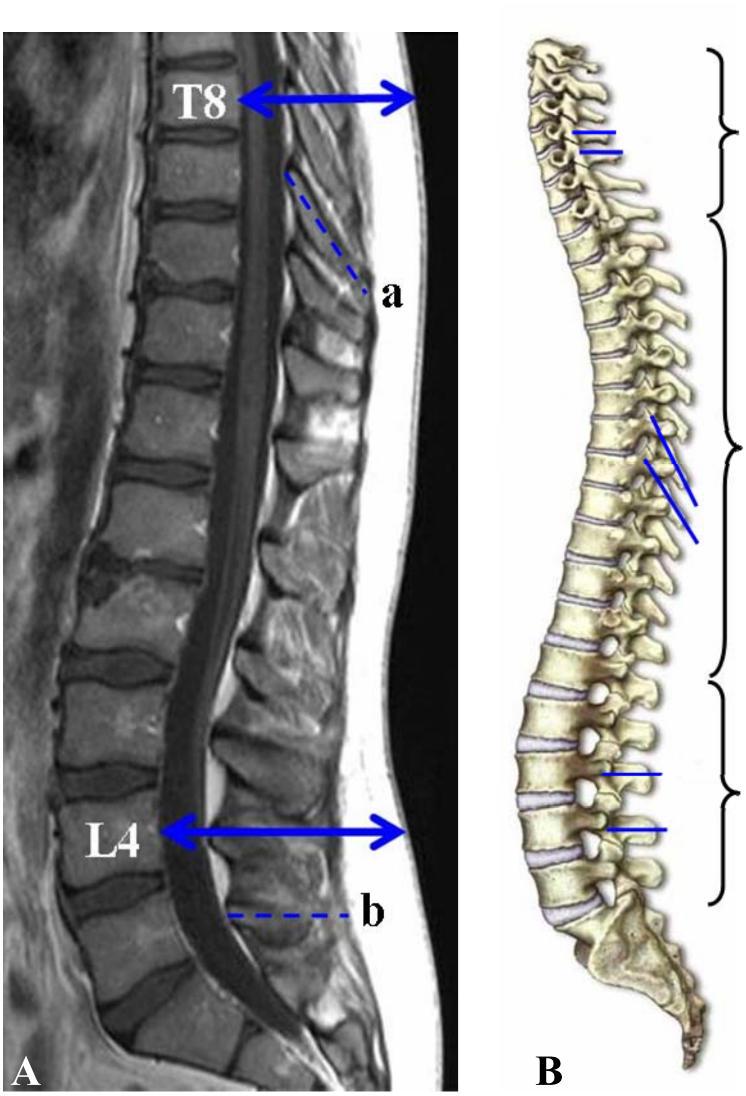

Figure VIII.1.1: (A): An MRI image revealing greater distance between the skin surface and posterior vertebral body at L4 compared to T8 (blue arrows). Caudal thoracic (a) and horizontal lumbar (b) spinous process orientation is shown (dashed lines). [Image modified from the prospective patient series] (B): Schematic representation of the spine which further demonstrates the caudal orientation of mid-thoracic spinous processes as compared with those in the cervical and lumbar regions [Image modified from www.eorthopod.com/images].

Hypotheses: A relationship was expected between the skeletal and surface lumbar lordosis curves measured in this female cohort, however it was not expected to be as strong as that previously identified for the thoracic region using similar methods (Goh et al. 2000; Weiss and

Elobeidi 2008). It was anticipated that sagittal alignment, as determined separately from the skin surface and vertebral bodies, would have a poor or no association.

Method: Sixty-nine women aged between 59 and 88 years of age (mean 71.9, SD 5.5) were examined for surface and skeletal sagittal curvature using rasterstereography and radiography, respectively. Subjects were participants in an institutionally-approved investigation examining factors relating to thoracic curvature and osteoporosis (Tan 2005). For this series, erect lateral radiography and rasterstereographic images were taken simultaneously with the subject in standing, arms elevated to approximately 60 degrees, whilst holding onto a pole positioned in front of them (Figure VIII.1.2).

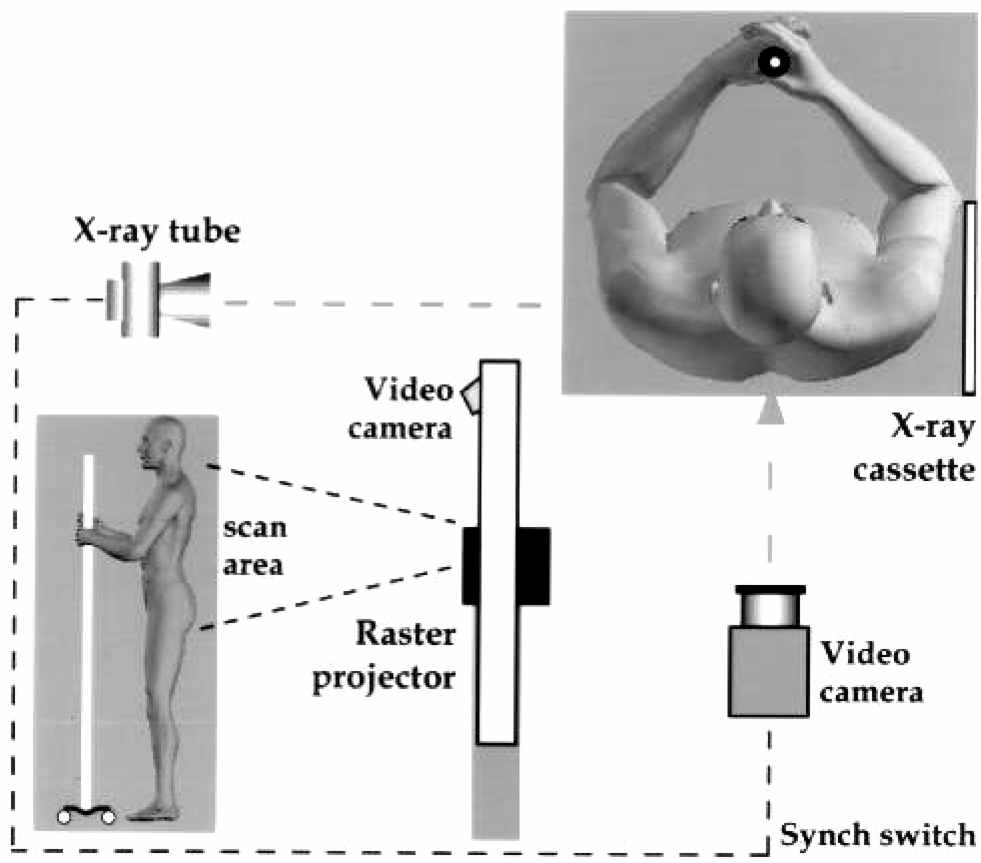

Figure VIII.1.2: Schematic representation of subject positioning for an archived series of 69 female subjects who were evaluated for surface and skeletal spinal curvature with simultaneous rasterstereographic and radiographic imaging, respectively. During image acquisition, subjects had their back fully exposed and were instructed to slightly tilt their chin toward their chest to enable surface vertebral prominens identification (for rasterstereography). [Illustration courtesy of KP Singer].

Tracings derived from the lumbar radiographic imaging allowed for manual measurement of the regional lumbar lordosis. Tangents along the superior end-plates of the first lumbar and first sacral vertebra were intersected via the 4-line Cobb method (Harrison et al. 2001) to derive skeletal lumbar lordosis. The angle created between the thoracolumbar (ITL) and lumbosacral (ILS) inflexion points was derived from the sagittal profile for the thoracolumbar curvature, from rasterstereography to indicate surface lumbar lordosis. Skeletal lumbar sagittal balance was measured using the LASD method described in Chapter 2 (Kawakami et al. 2002). Thoracolumbar sagittal balance (SB) was calculated using the values for trunk length (TL) and trunk inclination (TI) as derived from the body surface via rasterstereography according to the equation SB=TL(tanTI). These methodological aspects are represented in Figure VIII.1.3.

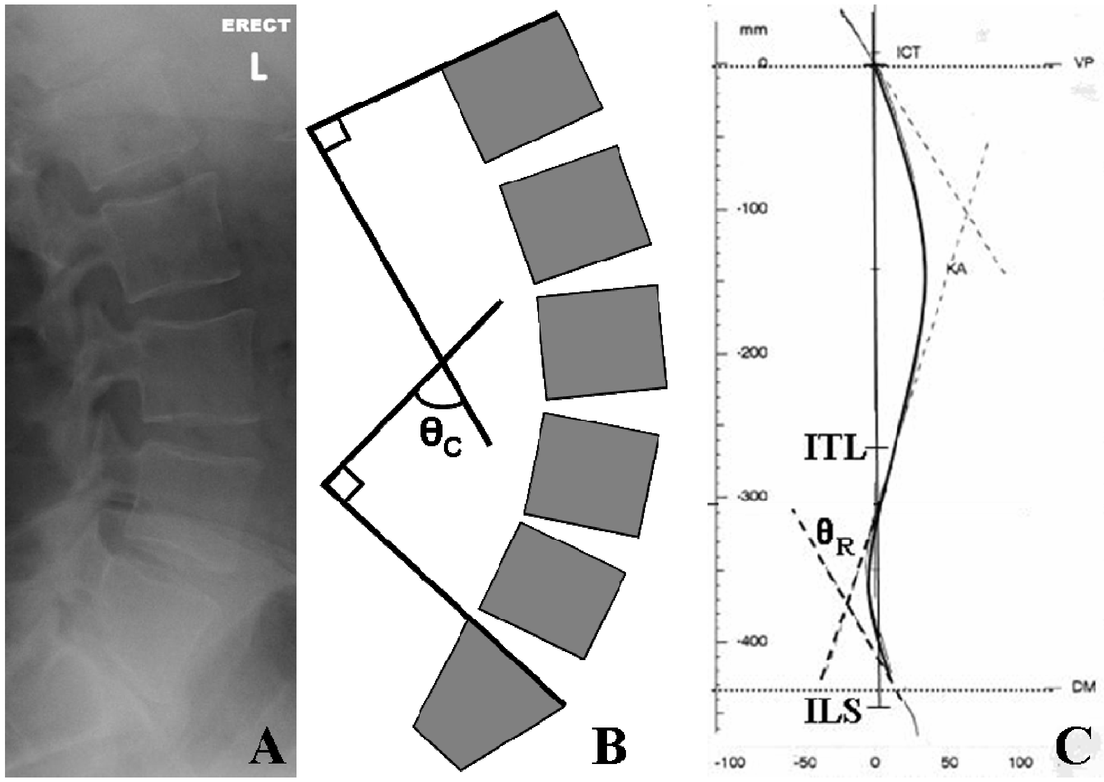

Figure VIII.1.3: Erect lateral radiograph (A) and schematic outline of lumbar vertebral bodies highlighting the four-line Cobb angle (θ_C) method for determining lumbar lordotic angle (B). Tangents are drawn from the superior end-plates of L1 and S1; perpendiculars from the tangents create the angle θ_C. Sagittal profile for the thoracolumbar curvature as produced using rasterstereography, where lordosis (θ_R) is derived from the angle created between the thoracolumbar (ITL) and lumbosacral (ILS) inflexion points (C).

Results: The average surface lumbar lordosis as measured via rasterstereography was 49.2 degrees (SD 10.9, range 21.2 to 74.5) while skeletal curvature as measured via radiography (L1-S1) revealed a lumbar lordosis of 58.1 degrees (SD 11.4, range 27.0 to 80.0). The mean difference was 9.0˚ ($p<0.0001$) between the two measures, with surface lordosis underestimating that derived skeletally. Surface and skeletal lumbar lordosis when measured simultaneously in this cohort of women revealed a modest correlation ($r=0.38$; $p<0.01$; 95%CI 0.16 to 0.57) (Figure VIII.1.4).

The average surface thoracolumbar sagittal balance as measured via rasterstereography for this series was 25.1mm (SD 26.8, range -38.7 to 87.2). The skeletal regional sagittal balance as derived from radiographs was -0.5mm (SD 24.9, range -56.5 to 60.6). The correlation between these two measures of sagittal balance was low (r=0.32; p<0.01; 95%CI 0.09 to 0.52). Surface derived trunk inclination also had a low correlation with skeletal lumbar sagittal balance (r=0.33; p<0.01; 95%CI 0.10 to 0.52).

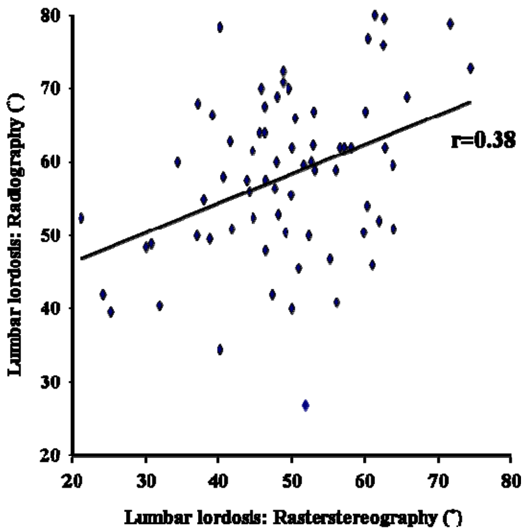

Figure VIII.1.4: Scatter graph representing the surface and skeletal lumbar lordosis from rasterstereography and radiography, respectively, for archived data from 69 women. Results revealed a modest correlation (r=0.38, p<0.001) between the two measures.

Discussion: Surface assessment of lumbar lordosis measured via rasterstereography underestimated skeletal lordosis derived through radiography by a mean of 9˚ (p<0.0001). The underestimation of surface curvature compared to that derived skeletally agrees with studies comparing the two in the cervical (Refshauge et al. 1994), thoracic (Willner 1981; Goh et al. 2000; Weiss and Elobeidi 2008), and lumbar (Willner 1981; Bryan et al. 1989) spines. Previous investigations employing rasterstereography for surface curvature and radiography for skeletal contour show a moderate relationship between the two in the thoracic region (Goh et al. 1999b; Weiss and Elobeidi 2008). The poor relationship (r=0.38) reported in the present study where rasterstereography was used to assess surface lumbar curvature, agrees with Bryan et al (1989) (r=0.30) who employed the flexirule for their surface measures based on the tangents traced from the L1 and S2 spinous processes that were located via palpation. The referenced end-points and tangential-based methods for these two studies that employ different instruments have similarities. The inferior results achieved for the lumbar spine suggest that surface and skeletal measures in this region represent two different curvature profiles. Caution is therefore needed in inferring vertebral alignment from observed surface contour.

The 'gold standard' measure used for the derivation of lumbar lordosis is based on that reported by Cobb, where the angle between vertebral end-plate tangents is measured (Cobb 1948). This method reflects end-plate tilt and end-plate architecture and as such does not reveal any regional curve characteristics. Elaboration on this limitation to the Cobb method for assessing spinal curvature has been made in Chapter 2.

The modest correlation (r=0.32) between surface and skeletal measures of sagittal balance assessed in this study was not too dissimilar from that shown for the lumbar lordosis (r=0.38). This may also indicate that surface and skeletal spinal profiles are different, and suggesting a need for caution when comparing the two measures. The rasterstereographically-derived measure considers the thoracolumbar spine from the vertebral prominens to the sacral dimples, while the radiologically derived measure is limited to the shorter lumbar region. Although the line of gravity approximates both of these, anatomical differences between the two exist. In their study comparing surface versus skeletal landmarks, Stonelake et al (1988) conclude that spinal length as measured from the surface between the vertebral prominens and the midpoint between the dimples, should not be used to reflect the distance between the C7 and S2 spinous processes based on the wide variation of the sacral dimple sites between cases (Stonelake et al. 1988). The potential for the variability of this surface parameter to affect the repeatability of measurement of sagittal balance and lordosis using the methods employed in the prospective investigation is acknowledged and explored further in Appendices VI.1 & VI.2.

Conclusions: Simultaneous imaging of surface (rasterstereography) and skeletal (radiography) lumbar lordosis revealed an underestimation of surface curvature in relation to the skeletal curve. Modest relationships between surface and skeletal lumbar lordosis and sagittal balance were shown (r=0.38 & r=0.32, respectively; $p<0.01$).

Acknowledgements: The author acknowledges that the radiographic and rasterstereographic imaging employed in this study was amassed by Dr. BK Tan for her PhD thesis investigation assessing the thoracic spine (Tan 2000), under the supervision of Professor Kevin Singer. The data described for the lumbar spine in the present study has not been previously reported and represents an original use of the sets of paired images. My thanks are extended to Mrs Kate Kirk from the Human Research and Ethics Committee at The University of Western Australia for providing the necessary permission to re-use the available image set. And to Dr Swithin Song, Deputy Head of Imaging Services, Royal Perth Hospital, for enabling use of radiographic materials.

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APPENDIX VIII.2

Lumbar vertebral morphometry: intra-regional differences in vertebral sagittal dimensions

Purpose: This morphometric study was undertaken to identify lumbar intra-regional differences in sagittal vertebral dimensions. Vertebral body waist (VBW), spinous process length (SPL) and the ratio between the two were investigated in a series of 29 unprovenanced osseous vertebral columns from the School of Anatomy and Human Biology, The University of Western Australia. The primary aim was to assess for variations to anteroposterior dimensions within the lumbar region, in order to better appreciate the relationship between the skin and vertebral body contour from in vivo studies. The relevance of this small study relates to the potential for divergence between measurements of surface and skeletal lumbar lordosis.

Background: Surface and skeletal curvature in the lumbar spine show a modest relationship [Appendix VIII.1; (Bryan et al. 1989)] that is weaker than that reported for the cervical (Refshauge et al. 1994) and thoracic regions (Willner 1981; Goh et al. 2000; Weiss and Elobeidi 2008). A postulated explanation for dissimilar surface and vertebral spinal contours is the variable length of the spinous processes, and therefore the approximating skin surface (Refshauge et al. 1994; Goh et al. 2000; Weiss and Elobeidi 2008; Crawford et al. 2009a). This is in addition to the influence of the potentially variable depths of any overlying soft tissues. Instruments measuring surface spinal curvature have been used as an alternative to radiographic measurement of vertebral contour in order to avoid patient exposure to ionising radiation and for the simplicity of use and improved clinical utility. How appropriate this is for lumbar curvature is questionable based on the modest correlation between the two (Appendix VIII.1; (Bryan et al. 1989). Using a transformative normalisation method, Bryant et al (1989) described greater error between surface and skeletal curvature in the lumbar region compared to that found in the thoracic spine (Bryant et al. 1989). This agreed with an earlier study by Willner (1981). Given skeletal curvature is derived from diverse vertebral body landmarks via various techniques (Chen 1999; Harrison et al. 2001), the dissimilar values reported for surface and skeletal lumbar contour may relate to the underlying morphology.

The superior VBW has been shown to increase caudally from L1 to L5 when measured directly from the vertebra (Berry et al. 1987), between L1 to L3 when measured from radiography (Gilad and Nissan 1986) and between L1 to L4 when measured from radiographs of cadaveric spines (Panjabi et al. 1992). A summary of these three earlier studies is presented in Table VIII.2.1. The spinous process length (SPL) when measured from the centre of the superior end-plate to its most inferoposterior tip, has been shown to increase slightly in the mid lumbar levels to peak at L3 (Panjabi et al. 1992). The spinous process distance (SPD) measured in the anteroposterior plane as the vertebra's full length, minus the VBW, has been reported as consistent for selected thoracic vertebrae (36 mm T2, T7, T12), but variable in the lumbar region (Berry et al. 1987). Berry et al

(1987) report the mean lumbar SPD values to be: L1 40.4mm; L2 40.2mm; L3 43.3mm; L4 42.6mm; and L5 28.0mm. This indicates the potential for intra-lumbar differences between the surface and vertebral contours.

Table VIII.2.1: Summarised results for three studies reporting dimensions for superior vertebral body waist (mm) [mean (SD)] for vertebras L1 to L5.

Study	n	M/F	Age	Method	L1	L2	L3	L4	L5
Gilad & Nissan, 1986	157	M	20-38 yrs	XR *in vivo*	33.5 (2.8)	34.4 (2.9)	34.7 (2.7)	34.3 (2.7)	34.2 (2.7)
Berry et al, 1987	30	M15 F 15	N/R	VB *Ex vivo*	31.9 (3.7)	33.3 (3.7)	33.9 (3.3)	34.9 (3.4)	35.1 (2.8)
Panjabi et al, 1992	12	M8 F 4	19-59 yrs	XR *Ex vivo*	34.1 (1.3)	34.6 (1.1)	35.2 (1.1)	35.5 (0.9)	34.7 (1.2)

n=number of subjects; Age=age range of subjects; XR=radiography; VB=direct from vertebral body

Hypotheses: Vertebral body widths were expected to increase caudally within the lumbar region, while the spinous process distance was expected to peak at L3 and be smallest at L5. It was anticipated that the present investigation would be most comparable to the findings reported by Berry et al (1987) who also measured directly from vertebrae.

Methods: A series of 29 complete sets of lumbar vertebra from unprovenanced osseous vertebral columns sourced from the School of Anatomy and Human Biology, were measured for vertebral body waist (VBW) and spinous process distance (SPD) using an NSK Max-Series electronic digital calliper (Japan Micrometer MFG Co, Ltd) (Figure VIII.2.1). Descriptive statistics were employed to present the data. Ratios between VBW and SPD were presented using box-plots.

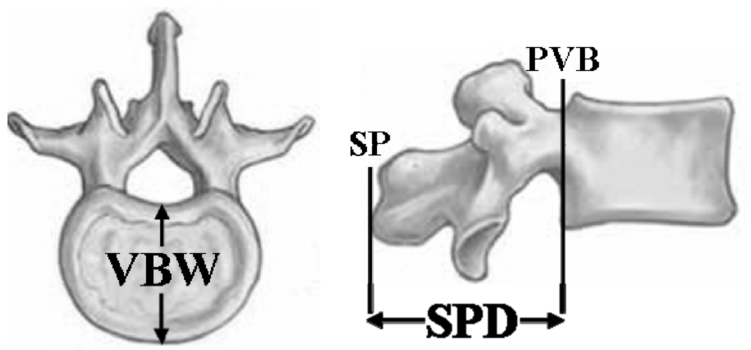

Figure VIII.2.1: Schematic representation of method employed to measure the vertebral body waist (VBW) and spinous process distance (SPD) (mm) in 29 unprovenanced lumbar spines. The elliptical posterior border/centrum was allowed for.

Results: Mean (SD) values for the VBW (mm) were: L1 [26.9 (2.9)]; L2 [28.5 (3.4)]; L3 [30.1 (3.2)]; L4 [30.9 (2.8)]; and L5 [32.2 (2.7)]. Mean (SD) values for the SPD (mm) were: L1 [37.5 (1.7)]; L2 [39.3 (4.1)]; L3 [39.4 (4.0)]; L4 [37.5 (5.2)]; and L5 [33.7 (5.1)]. These results are both presented in Figure VIII.2.2. When these two values were summed for each lumbar vertebral level, the total lengths increased from L1 to peak and L3, and then reduced again to L5. The results for the ratio between VBW and SPD per vertebral level are presented in Figure VIII.2.3 and reveal and increasing craniocaudal trend.

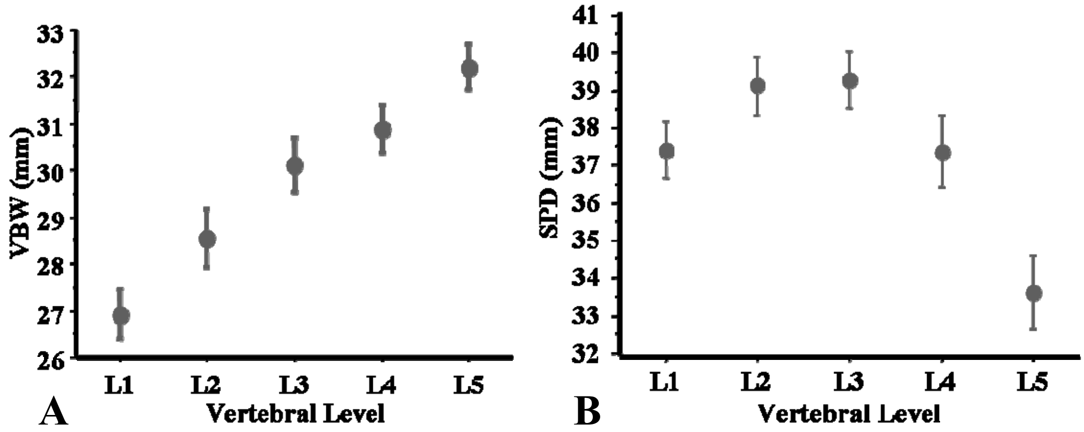

Figure VIII.2.2: Mean vertebral body waist (VBW) (A) and spinous process distance (SPD) (B) (±1SEM) from a series of 29 unprovenanced lumbar spines according to vertebral level.

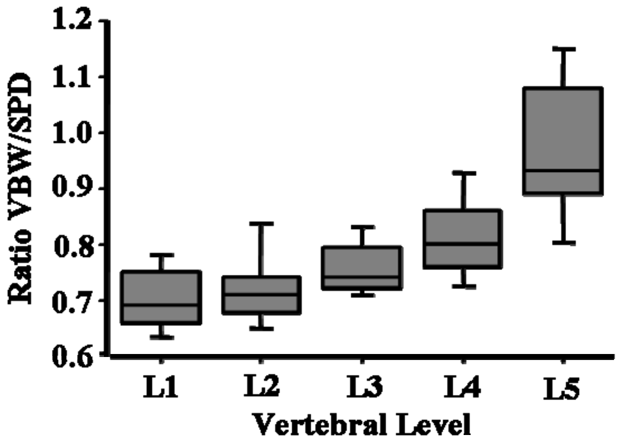

Figure VIII.2.3: Ratio of vertebral body waist (VBW) and spinous process distance (SPD) per vertebral level

Discussion: The results of this investigation are in agreement with the Berry et al (1987) study that also measured direct from the vertebrae. A caudal increase in vertebral body waist and a peak of the spinous process distance and total AP vertebral length at L3, confirm the variability of these dimensions in the lumbar region. Panjabi et al (1992) described the middle lumbar region to be characterised by the greatest end-plate areas and the longest spinous process length, which they postulate is related to L3 representing the apex of the natural lordotic curve. The results of the present study appear to agree with this notion. The increasing VBW/SPD ratio described in this study add further evidence for the intra-regional morphometric variability within the lumbar region, which may contribute to explaining why the correlation between surface and skeletal lumbar curvature is only modest (Appendix VIII.1; (Bryan et al. 1989).

This is in contrast to the higher correlating thoracic region where sagittal AP vertebral dimensions appear more consistent (Berry et al. 1987). Based on these morphometric lumbar differences it appears reasonable to accept that surface and skeletal lumbar contours represent different curvature profiles. The intraregional differences noted in this series of lumbar spines may indicate the potential for variability between skin surface and skeletal lumbar contours. Further study using MRI cases would be helpful to elaborate skin to skeletal dimensions. The study presented in Appendix VIII.3 explores this aspect further.

Conclusions: Direct measurement from ex vivo lumbar spines indicate increased vertebral body waist dimension between L1 to L5. The spinous process distance and total vertebral AP length appear to peak at L3, while being smallest at L5.

Acknowledgements: The author would like to extend her gratitude to the staff of the School of Anatomy and Human Biology, Faculty of Life and Physical Sciences, The University of Western Australia, for facilitating the use of the vertebral columns and laboratory space employed to undergo this study.

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APPENDIX VIII.3

Skin and subcutaneous tissue thickness overlying thoracolumbar spinous processes

Purpose: An investigation was undertaken to compare the skin tissue thickness overlying the spinous processes in the thoracic and lumbar regions. Values for spinal curvature are different when derived from the skin surface compared to directly from the vertebral bodies, with a poor correlation between surface and skeletal measures reported for the lumbar region (Bryan et al. 1989) (Appendix VIII.1). Investigators have suggested that this relates in part to variable thicknesses of subcutaneous tissues that overlie the spinous processes, which are believed to be thickest in the lumbosacral region (Bryan et al. 1989; Mannion et al. 2004). Searches of fundamental and related spinal curvature literature, would suggest that this premise has not been formally examined. The present study sought to provide preliminary information, based on thoracolumbar magnetic resonance imaging (MRI), to quantify differences in subcutaneous tissue thickness along the para-sagittal region of the axial thoracolumbar spine.

Background: Appendices VIII.1 and VIII.2 have previously provided the requisite background information underpinning this study.

Hypothesis: Subcutaneous tissue overlying the spinous processes was expected to be thicker in the low lumbar region than for the upper lumbar or thoracic levels.

Method: Ten female (otherwise unprovenanced) sagittal thoracolumbar MRIs from an existing series were examined for subcutaneous tissue thickness overlying thoracolumbar spinous processes. Subjects were participants in an institutionally-approved investigation examining patterns of disc degeneration in the thoracic region, the results of which have been reported in the literature (Tan et al. 2001). Subjects were imaged using a recumbent (supine) MRI. Ten digital images were randomly selected from the original series based on fulfilling inclusion criteria. Only images that spanned thoracic and complete lumbar spines were assessed. Incomplete thoracic spines were included if they had all levels distal to and including T7 or the kyphotic apex if it was higher. Images that reflected overt disease of the spine were excluded. Digital images were processed using MxLiteView Version 1.25 (Philips Medical Systems, Cleveland, USA). Images were loaded and the best slice defining the median spinous processes for all levels was selected for measurement. The programme distance tool was used to derive two length variables: between the most superficial aspect of the spinous process (SP) and the outer skin surface; and the mid-point of the posterior vertebral body (PVB) and the outer skin surface. Measurements were derived for skeletal levels: S2 (or sacral base for PVB), L5, L4, L3, L2, L1, T12, T11, T10, T9, T8, T7 and the kyphotic apex (KA) vertebra if it was higher than T7. The level of the KA was selected as the peak of the dorsal convexity through visual inspection of the entire available curve. Individual data were plotted as a line chart with descriptive statistics used to present group results. Group means were cautiously applied given the magnification of individual images was unknown. Despite this means were employed as a reflection of the relative intra-individual differences between segments. The nonparametric Wilcoxon signed rank test was employed to assess for the significance of any differences between L5, L3, L1, T10, T8 and KA values. A probability of $p<0.05$ was used as the criterion to represent meaningful differences.

Results: Individual and group results are presented in Figure VIII.3.1. Table VIII.3.1 presents the mean (SD) results for the 10 MRI studies measured.

Table VIII.3.1: Mean (SD) results for: skin thickness overlying thoracolumbar spinous processes (Skin), horizontal distance between the posterior vertebral body and the skin surface (PVB-Skin), and the ratio between both variables (PVB-Skin:Skin) from the kyphotic apex (KA) to the sacral base. These results were based on measurements from 10 sagittal MR images.

	Skin	**PVB-Skin**	**Ratio**
Kyphotic Apex	8.5 (4.6)	42.9 (5.8)	6.3 (2.8)
Thoracic 7th Vertebra	8.4 (4.6)	42.9 (5.8)	6.4 (2.8)
Thoracic 8th Vertebra	9.2 (5.2)	42.9 (5.6)	5.9 (2.7)
Thoracic 9th Vertebra	8.8 (5.1)	43.0 (6.1)	6.3 (3.3)
Thoracic 10th Vertebra	8.5 (4.0)	45.1 (6.8)	6.0 (2.0)
Thoracic 11th Vertebra	9.4 (5.2)	46.2 (7.0)	6.2 (2.8)
Thoracic 12th Vertebra	10.7 (7.1)	49.9 (8.7)	6.4 (3.5)
Lumbar 1st Vertebra	10.4 (7.4)	52.3 (10.3)	6.6 (2.9)
Lumbar 2nd Vertebra	10.4 (8.4)	55.1 (10.9)	7.4 (4.0)
Lumbar 3rd Vertebra	14.3 (9.8)	58.8 (13.5)	5.0 (1.6)
Lumbar 4th Vertebra	20.3 (11.1)	63.5 (14.6)	3.9 (1.9)
Lumbar 5th Vertebra	21.3 (11.3)	66.4 (15.0)	3.8 (1.8)
Sacral 2nd Vertebra	21.2 (10.6)	59.7 (13.0)	3.3 (1.3)

Subcutaneous tissue thickness (mm) (mean ± SD) overlying L4 (20.3 ± 11.1), L5 (21.3 ± 11.3) and S2 (21.3 ± 10.6) were clearly greater than for the rest of the thoracolumbar levels measured. The distance between the PVB and the skin was also greater at the low lumbar levels. The greatest variability in skin thickness and PVB-Skin distance between cases was seen in the lumbar segments, particularly at L5. Significant differences existed for skin thickness between L3, L1, T10, T8 and thoracic apex when compared to L5 ($p<0.05$). No difference was detected between levels above and including L3, or between L4, L5 and S2.

Discussion: This small study revealed an increased subcutaneous tissue thickness in the low lumbar spine as compared with the upper lumbar, lower thoracic and kyphotic apex levels.

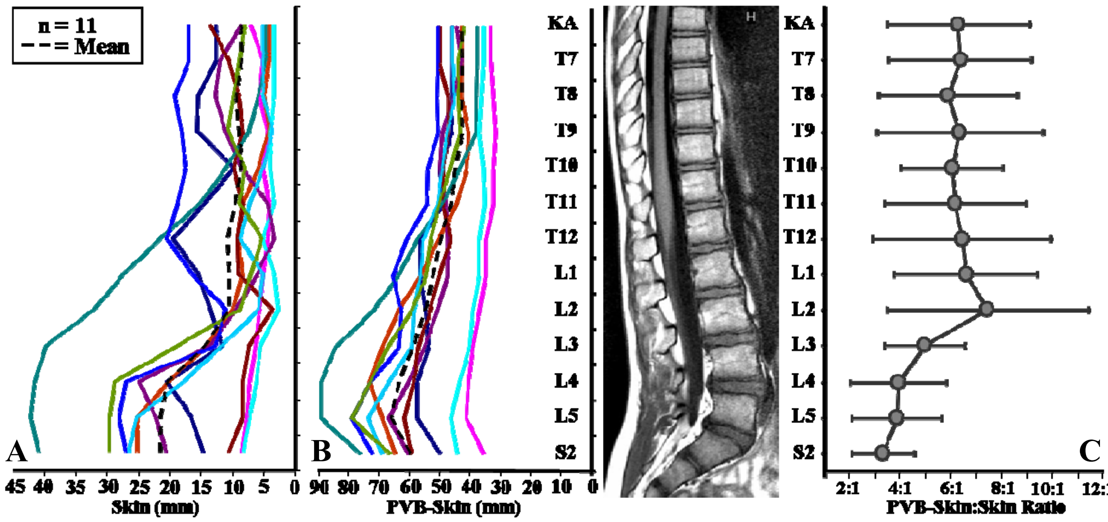

Figure VIII.3.1: Individual results for subcutaneous skin tissue thickness (A), posterior vertebral body to skin distance (PVB-skin) (B) and the ratio between the two variables (PVB:Skin) (C) along the thoracolumbar spine in 10 females as determined by measurements derived from sagittal MRI. Group mean results are indicated by the dashed line in A and B, and by the dots (± 1SD) in C.

Although authors have speculated that this might be true (Youdas et al. 1995; Mannion et al. 2004; Youdas et al. 2006), no formal study was identified to support the premise. This study provides additional understanding as to why differences between surface and skeletal spinal contour exist, at least in women. In particular, it provides a reason to explain why the relationship between the two in the lumbar region is more divergent than for thoracic levels (Appendix VIII.1 introduction).

Two obvious limitations to this investigation relate to using images derived from recumbent subjects during MRI where inter-individual image scaling was uncertain. Recumbent MRI requires the subject to lie supine on the back with legs in extension. This position results in the dorsal skin surface being variously compressed at contact points with the support. Give the natural dorsal convexity of thoracic kyphosis, the mid-thoracic spine is more likely to be compressed than the concave lumbar lordosis. It might also be argued that the sacrum represents another region of contact or at least probable tissue compression through the buttocks. The vertebral levels used in this study that were most likely to have compressed subcutaneous tissue by this rationale, were KA-T9 and S2. Therefore those levels may be expected to have slightly thicker midline subcutaneous tissues than this study reports. Mid thoracic levels might therefore not be as different from the low lumbar levels, however thicker tissue overlying the sacrum further supports the study hypothesis. Intuitively, in supine many of the thoracolumbar spinous processes would not be in contact with the support at all, due to other structures like the erector spinae or scapulothoracic muscles being more posterior and therefore preferentially load-bearing. Perhaps a balance between these two notions allows acceptance that the findings are reasonable.

The mean results have been presented more as a qualitative indication of group behaviour with the values themselves not intended for actual comparison with other or later investigations. In preference, the reported ratios might offer a suitable alternative. Further work assessing the anatomical feature reported here should employ upright MRI as an improved imaging source. Standardised scaling measures should also be introduced to expand the utility of the derived data.

This study lends preliminary support for the idea than lumbosacral midline tissues are thicker than those found in the upper lumbar or thoracic levels caudal to the kyphotic apex.

Conclusions: Subcutaneous tissue overlying the spinous processes was thicker in the low lumbar region than for either the upper lumbar or thoracic levels. Normative values for tissue thickness have not been reported due to methodological limitations. The ratio between the posterior vertebral body-to-skin and skin thickness offers a potentially suitable comparator for future investigators. Recommendations for further study have been made.

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APPENDIX IX

Comparison of the film edge of radiographic images obtained at fourteen Perth Radiology Clinics with a vertical plumbline

Purpose: To assess radiographic images obtained from fourteen Perth Radiology Clinic (PRC) sites in order to compare their longitudinal edge to a vertical plumbline. The primary aim was to test the assumption that a radiography longitudinal film edge is vertical.

Background: An intention in conducting the radiographic outcomes assessments for the main thesis investigation was to accord with the surgeon's routine protocol. This involved patients selecting the site to action their radiographic referral, which introduced a step for the investigator that necessitated collaboration with a private radiology practice comprising several site locations and therefore a potential for various radiographers, within and between sites, to execute the standing lumbar plain imaging. The possibility for this process to introduce a degree of variability to the methodology for radiography was identified a priori and mitigating procedures put in place to reasonably standardise the radiography method employed. Patient-positioning and image distance guidelines were attached to referrals (Appendix IV.2) in order to communicate with each radiographer performing the imaging.

Additional consideration was paid to the derivation of skeletal measurements where the edges of the radiographic images were used for reference. In particular, the measurement of lumbar regional sagittal balance (RSB) was calculated using the LASD method (Kawakami et al. 2002) by referencing a vertical plumbline centred from the first vertebral body in relation to the sacrum (refer to Figure 3.3). This variable is influenced by inclination of the person's trunk with respect to the vertical and therefore an absolute plumbline is necessary. Where the primary focus for a study is radiographic or skeletal variables based on imaging, investigators may elect to use a single machine for all cases wherein appropriate controls can be accommodated and monitored; this was not the case for the present study where several locations were randomly used. When deriving measurements from erect lateral lumbar radiographic images, the edge of the film is generally assumed to be vertical (Kuklo 2008), particularly in the absence of any introduced radio-opaque scaling markers. This assumption therefore relies on the accuracy of the system, which can be influenced by the: buckey being accurately fixed to either the floor or wall surface; digital plate being automatically or manually positioned to true vertical within the digital reader; digital reader being automatically or manually loaded into the cassette to assume a squared position abutting the cassette edges; and the cassette being automatically or manually inserted into the buckey squarely. These four aspects, as represented in Figure IX.1, play a role in image production and have the potential to affect the verticality of any derived image. Accounting for each of these separately was not possible, however an indication of the composite effect on verticality for each buckey employed was of interest.

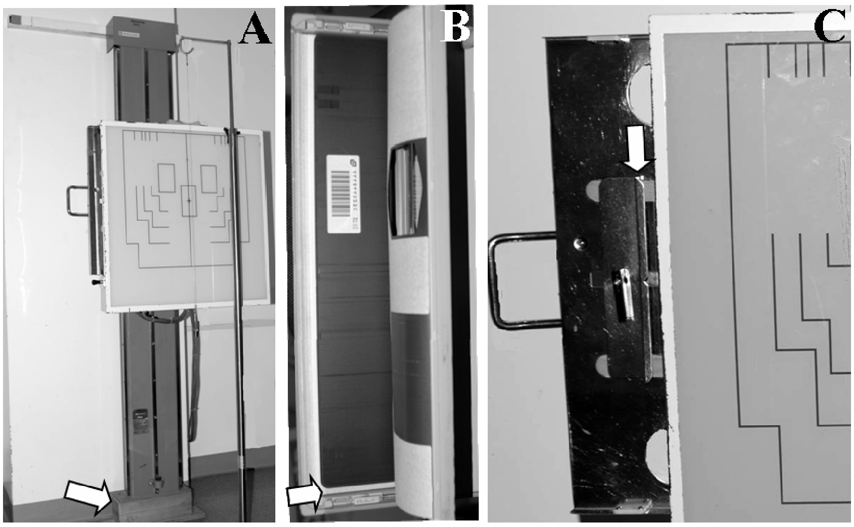

Figure IX.1: Schemmatic representation of the potential areas in the process of radiographic image production where deviations from true vertical are possible: (A) Buckey being fixed to the floor [white arrow] (or in some cases the wall); (B) Reader being manually or automatically loaded squarely within the cassette [small capacity for deviation from the cassette edge is noted by the white arrow]; (C) Cassette being manually adjusted (or automatically loaded) to squarely sit within the buckey-plate [white arrow]

Of particular significance in the main investigation for this thesis was that the surgical patients for the study were referred for radiographic imaging at any of fourteen private radiographic clinics of their choice. This meant that measurements from radiographs used in time-point comparisons might have been imaged at different locations using different machines. What variability in the verticality of images existed between sites was therefore of interest, and whether there was potential to apply a scaling factor to data from each site in order to accommodate for any variability was explored.

Hypothesis: This collateral investigation was based on two hypotheses: that there would be no difference in angulation between the vertical edge of a digital film and a radio-opaque plumbline imaged by the system; and that therefore the verticality of produced images is equivalent across all 14 PRC locations.

Methods: Fourteen Perth metropolitan PRC locations were identified to have been visited by one or more patients in the main study on referral for preoperative imaging (Figure IX.2). A radiographic image was requested from each of these sites by the author, to be taken according to the routine protocol used at that location for a standing lateral lumbar adult referral received with the studies positioning guidelines attached. Any x-ray machine within each practice location that might have been used for the purpose was included in the analysis. Based on this request, it came to light that two sites that the author knew had been frequently used by the patient cohort, had two or more machines each that were randomly and equivalently used for the purpose, depending on availability.

KEY

A1	Joondalup Health Campus (JHC)
A2	Joondalup (J)
B	Beldon (B)
C	Nollamarra (N)
D	Innaloo (I)
E	Subiaco (S)
F	The Mount Hospital (Mt)
G	Midland (M)
H	Bethesda Hospital (BH)
I	South Perth Hospital (SPH)
J	Bentley Health Campus (BHC)
K	Booragoon (BG)
L	Armadale-Kelmscott (AK)
M	Rockingham (Ro)

Figure IX.2: Map of the metropolitan area in Perth, Western Australia depicting fourteen Perth Radiological Clinic sites where radiographic imaging of a suspended plumbline was conducted. Patients in the surgical cohort were referred for standing lateral lumbar radiography at their choice of each of these locations. Plumbline assessment for each site was undertaken to better appreciate the vertical variability of the produced images between sites.

Although the derived images for this verticality study could be marked on site according to which machine was used, it was explained to the author by the attending radiographers, that all other digital images received by the neurosurgeon from PRC would contain no reference to the specific machine used.

Sixteen images from 16 machines across the 14 sites were taken. Each image included a radio opaque plumbline (a weighted wire string) that was suspended from a drip-stand positioned centrally in the image-field by the author (Figure IX.3). The plumbline was selected to represent true vertical. A digital photograph of each setup was taken. Radiographers were asked to employ the exposure that best approximated what they would use for standing lumbar imaging of a patient. The single digital radiographic image achieved for each buckey machine was saved in JPEG format. Each digital image was viewed on the same monitor and assessed using the programme employed in the radiography component of the main investigation (refer to Chapter 3). The angle between tangents of the radio-opaque plumbline and the left-side vertical film edge was measured. This was done 5 times per image to obtain a mean value of deviation from the vertical for each buckey assessed. This stage was repeated a week later in order to assess the intra-rater repeatability of the method. Descriptive statistics were used to indicate the variability in the 5 measures (repeatability of application of the digital programme) and between sites. Wilcoxon's signed rank test was used to compare serial values ($p<0.05$).

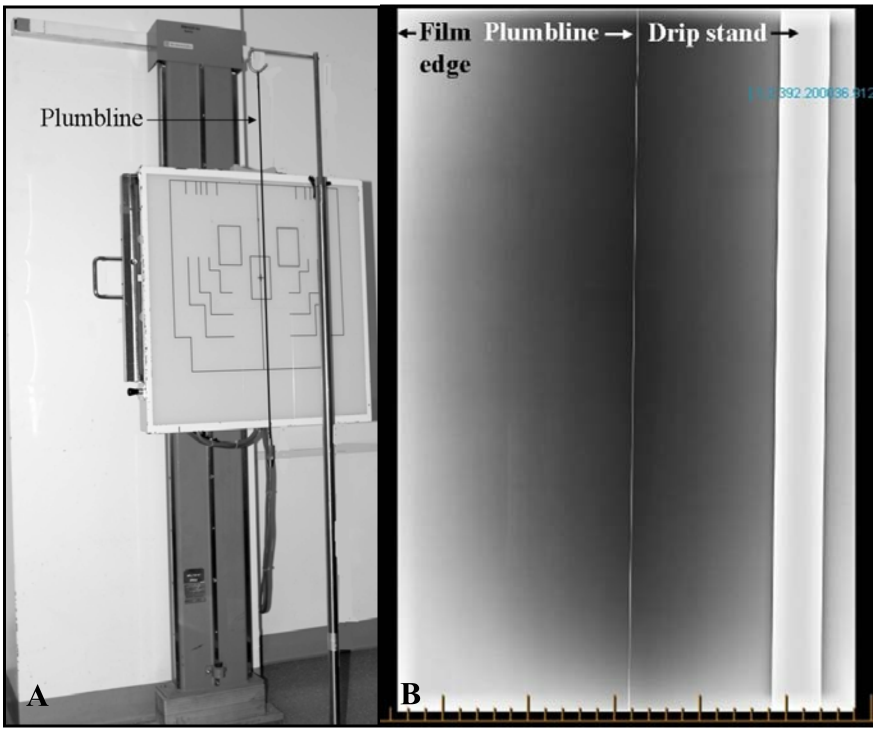

Figure IX.3: Demonstration of the plumbline setup on a drip-stand positioned immediately in front of the radiography buckey (A), and an example of the JPEG file of the derived image from which measurement of the angle between the film edge and plumbline were subsequently taken.

Table IX.1: Mean (SD) of five measurements of the angle defined by tangents along the left longitudinal radiographic digital image edge and a radio-opaque plumbline that was imaged according to a standard protocol for lateral lumbar radiography at 14 Perth Radiological Clinic (PRC) sites. These values indicate the verticality of images produced at the different locations used by the prospective cohort in the main investigation. Negative values indicate anti-clockwise deviation from vertical.

PRC Site	First	Second	Δ
Armadale-Kelmscott	0.44 (0.06)	0.40 (0.01)	0.04
Beldon	0.39 (0.03)	0.38 (0.02)	0.01
Bentley Health Campus	0.45 (0.01)	0.45 (0.01)	0
Bethesda Hospital	0.05 (0.04)	0.04 (0.03)	0.01
Booragoon	-0.26 (0.03)	-0.26 (0.02)	0
Innaloo	-0.04 (0.04)	-0.05 (0.02)	0.01
Joondalup Health Campus	0.19 (0.02)	0.21 (0.01)	0.02
Joondalup	0.75 (0.01)	0.75 (0.01)	0
Midland	0.70 (0.02)	0.70 (0.01)	0
Mount Hospital	0.42 (0.04)	0.42 (0.01)	0
Nollamarra (1)	0.93 (0.04)	0.93 (0.02)	0
Nollamarra (2)	0.42 (0.01)	0.42 (0.01)	0
Rockingham	-0.27 (0.03)	-0.30 (0.01)	0.03
South Perth	0.18 (0.04)	0.19 (0.02)	0.01
Subiaco (1)	0.73 (0.01)	0.73 (0.01)	0
Subiaco (2)	0.64 (0.04)	0.65 (0.03)	0.01
Mean	**0.36 (0.36)**	**0.35 (0.36)**	**0.01 (NS)**

First=first set of measures; Second=second set of measures taken one week later; Δ=difference between the two time-points; NS=not significant ($p<0.05$); (1)(2)=values for both machines per site. Mean (SD; range) angles measured for all 16 machines at the 14 locations were 0.36º (0.36; -0.27 to 0.93) and 0.35º (0.36; -0.30 to 0.93) degrees for the first and second repeat measure time-points, respectively. The repeatability of intra-session values revealed a mean standard deviation of 0.03º (range 0.01 to 0.06) and 0.02º (range 0.01 to 0.03) for the first and second set of measurements, respectively. There was no significant difference between the values obtained at both time-points ($p<0.05$).

Results: Table IX.1 presents mean (SD) angle per machine as measured at both time-points. The mean (SD) difference between the first [0.36˚ (0.36)] and second [0.35˚ (0.36)] measurements was 0.01˚ which was not significant. Vertical angulations for each machine ranged between an anti-clockwise deviation of 0.27˚ to a clockwise deviation of 0.93˚ when first measured, and between -0.30˚ and 0.93˚ when measured again. This indicates a potential for deviation from vertical within 1.2-1.3˚ across all radiography sites measured.

Discussion: This study revealed less than one degree deviation of the edge of the film from true vertical at each site when compared to a radiographically imaged plumbline. When all 14 sites are considered together, the potential for deviation from true vertical between images obtained from each of these sites is in the region of 1.25˚. Despite this seemingly small error, the study hypothesis purporting equality between the two should be rejected based on the data from 14 radiology sites assessed. The small angle may impact on serial measurements assessing sagittal inclination of the lumbar region [as necessary to define regional sagittal balance via the lumbar-axis-sacral-distance (LASD) method; (Kawakami et al. 2002)] because trunk inclination is also typically small (-5º-5º; Chapter 5). This range is based on the surface curvature measurements derived via rasterstereography for healthy volunteers that were used to calculate sagittal balance reported in Chapter 5. A 1.25º system error may prove a significant influence on results. By way of example, for cases with a trunk length [from the vertebral prominens to the sacrum] of 500mm, a 1.25˚ trunk inclination would equate to a thoracolumbar sagittal balance of 10.9mm. This represents nearly half (12.5mm) of the range in one direction from the vertical considered normal for sagittal balance (Jackson and Hales 2000; O'Shaughnessy and Ondra 2007). However, the influence of the same degree of angulation from the vertical would be expected to be considerably less when the shorter length of the lumbar region is considered. If the lumbar length from the centre of L1 to the sacral base is 200mm, sagittal balance, as determined for the region using the LASD method based on a 1.25˚ inclination from the vertical, would be 4.4mm. Although this value appears small and less than one quarter of that considered normal for sagittal balance, it may influence the interpretation of any noted differences reported over time in the surgical cases reported in the main investigation.

Spinal balance relating to the sagittal vertical axis has historically been reported based on studies assessing more dramatic deformities like scoliosis (Kuklo 2007; O'Shaughnessy and Ondra 2007). As such, the extent of trunk deviation from the vertical would expected to be greater than in cases receiving ISP or lumbar decompression surgery for lumbar degenerative disorders. Sagittal balance appears an increasingly popular radiographic variable being reported in cases after less invasive or unisegmental lumbar surgeries like single level fusion (Kawakami et al. 2002; Mac-Thiong et al. 2008; Endo et al. 2010). Results of the present study indicate an aspect of system error that would need to be considered when interpreting radiographic images where the assumption of a vertical image edge is made. The inclusion of a plumbline vertical reference within the image may be necessary.

Intra-rater repeatability of the method used in this collateral investigation was reasonable, with no significant difference in measurements taken by the author one week apart. The author has been unable to locate published studies investigating a fixed (floor or wall) buckey's verticality, which may confirm that it is an assumed parameter.

Conclusions: Radiographic images of a vertical plumbline used to assess the verticality of 16 buckey's within a Perth private radiological practice, showed 1.25º variability from true vertical across the 14 sites. This small deviation has the potential to influence measurements referencing inclination of the trunk.

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APPENDIX X

Pain and function a year after decompressive disc surgery: cases augmented with the DIAM interspinous implant versus those receiving microdiscectomy

Purpose: An investigation was undertaken to assess clinical outcomes after decompressive lumbar surgery for herniated nucleus pulposus (HNP) in order to compare two patient cohorts who received different surgery from the same neurosurgeon. Both cohorts comprised consenting participants in separate institutionally-approved observational longitudinal studies from the University of Western Australia, that were undertaken in collaboration with the same private neurosurgical practice in Perth. The first group of subjects from an earlier investigation received microdiscectomy in treatment of their disc pathology, while the second group, associated with this thesis study, underwent microdiscectomy augmented with the insertion of a DIAM interspinous implant at the index segment. Assessing a comparison group to better appreciate the clinical effects of the decompressive microdiscectomy technique employed by the surgeon in the main investigation, was considered valuable in the absence of a suitable control group. Although the two groups assessed here were not assumed to be identical, it was felt that the microdiscectomy cohort represented a series of patients receiving decompression that may have represented a surgical precursor to augmentation with the DIAM based on the clinical reasoning of the same neurosurgeon.

Background: Interspinous devices are purported to serve as an alternative means of preventing, or at least limiting the incidence of reherniation after primary disc excision (Senegas 2002). This is based on the premise that ISP-induced distraction of the posterior column results in unloading of the posterior disc anulus (Swanson et al. 2003; Wilke et al. 2008). The Device for Intervertebral Motion (DIAM) was developed by Jean Taylor in France and comprises a silicone-based interspinous spacer whose indications include: disc degeneration, mild degenerative spondylolisthesis, disc herniation and bulging disc that results in foraminal, lateral recess or central canal stenosis (Medtronic 2006; Taylor et al. 2007). The DIAM can be employed in isolation, or more commonly as an augmentation to other minimally-invasive decompressive lumbar surgeries (Schiavone and Pasquale 2003; Mariottini et al. 2005; Medtronic 2006; Taylor et al. 2007). As such, whether any clinical benefit exists in using a DIAM compared to employing decompressive surgery alone is of importance from a patient outcomes perspective. The neurosurgeon involved with both cohort studies increasingly employed DIAM-augmented surgery as a progression of his surgical planning. This process occurred toward the end of the microdiscectomy study and prior to the DIAM one.

Hypotheses: The presence of a DIAM would reduce the likelihood for repeat surgery at the index HNP segment within a year postoperatively and lead to superior outcomes compared with the group who received microdiscectomy alone. Improvements would be in accord with minimally clinically important difference recommendations (Bombardier 2000; Bombardier et al. 2001; Dworkin et al. 2008).

Methods: All subjects were consenting participants in two separate studies and who had received lumbar surgery in treatment of HNP: microdiscectomy alone (Lynn 2009a); or microdiscectomy and DIAM implantation (current thesis investigation). Baseline and follow-up data for the Lynn study preceded the current investigation in excess of one year, with subject numbers in the former diminishing as the DIAM implant became increasingly employed by the surgeon. Both sets of clinical outcomes were prospectively collected as part of each original investigation and retrospectively audited for use in the present study. Superior information relating to case specifics was known for the DIAM group, which allowed a more detailed description of each case. Pain [VAS (visual analogue scale) back and leg] and function [Micro=Roland-Morris Disability Questionnaire (RMDQ %); DIAM=Oswestry Disability Index (ODI %)] were each assessed as part of a patient-reported heath related quality of life questionnaire. Higher percentages for these three scores represented poorest function and worst pain. The questionnaires were applied at four time-points: preoperative baseline, 4-6 weeks, 6 months and 12 months postoperatively.

Descriptive statistics were used to represent means and standard deviations of demographic and baseline pain and function data. Frequency counts were used to indicate repeat or redo surgical interventions. Serial changes were described with change scores. Group pain and function were presented as actual change at 12 months from baseline (12m-B), and relative to preoperative levels [(12m-B)/B]. Comparisons of serial change for function, back and leg pain between the two surgical groups were applied using unpaired t-tests. Box-plots were used to illustrate the intra and inter-group data. Serial change was assessed using the Scheffe's post-hoc test (repeated ANOVA). Statistically meaningful differences were defined by $p<0.05$.

Patient Cohorts:

Microdiscectomy alone (Micro): Forty-eight patients (18 females, 30 males) underwent microdiscectomy during a period of 18 months (July 2005 to December 2006) in treatment of HNP. The mean (SD; range) age for the group was 45.0 years (SD 14.2; 20-75 yrs). Surgery was performed at L3/4 in 3 patients, L4/5 in 24 and L5/S1 in 21 cases. Patients who received microdiscectomy in isolation numbered 14, while 34 received additional access-related surgery that had the potential for decompression benefits, including various forms of laminotomy [outlined in Chapter 2.2].

DIAM-augmented disc decompression (+DIAM): Twenty-nine patients (10 females, 19 males) were selected from the main prospective study group through the process of serial elimination from the whole cohort of 81 patients for whom 12 month outcomes data were available (demonstrated in Figure X.1). Patients were selected in the following order: original 81 cohort;

those categorised with predominant disc pathology (n=43); and who received single-level surgery (n=29). Patient registration for the main thesis investigation occurred between June 2007 and June 2008. Within this group of patients cases had been diagnosed with foraminal stenosis that was associated with (n=7) or without (n=22) coexisting degenerative spondylolisthesis. Of each of these clinical diagnoses, cases had received DIAM implantation either with microdiscectomy in isolation or in combination with access-related decompressive laminotomy. The latter information was sourced by the author from the perioperative report written by the surgeon at completion of the surgery. Specific details of the extent of laminotomy were not included.

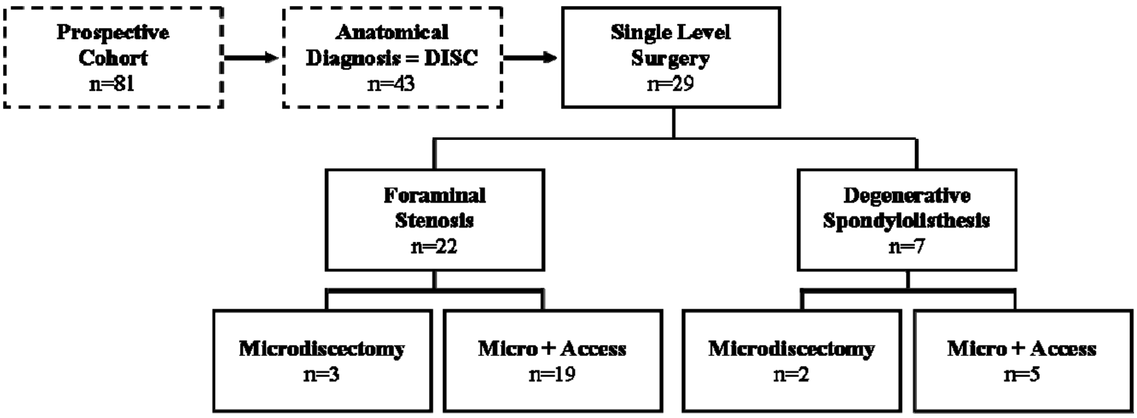

Figure X.1: Organisation chart demonstrating the elimination process used for selecting appropriate patients (n=29) from the main study prospective cohort (n=81). Clinical diagnoses and surgical approach techniques employed are indicated.

The mean (SD; range) age for the group was 42.0 years (SD 11.2; 20-64). The primary level to which the surgery was directed was at L3/4 in 1 patient, L4/5 in 8 and L5/S1 in 20 cases. By proportion there were more L5/S1 surgeries in the DIAM cohort than the micro-alone group. Patients in the DIAM-augmented group who received microdiscectomy in isolation numbered five, while 24 received additional access-related laminotomy surgery that had the potential for decompression benefits.

Results:

<u>Baseline comparisons:</u> No difference between the preoperative mean ages of the two groups existed ($p=0.34$). Patient-reported preoperative function was not significantly different [Micro=RMQ 45.9% (SD 22.4), DIAM=ODI 42.7% (SD 19.1); $p=0.52$]. Patient-reported preoperative back pain was not significantly different [Micro=VAS 51.9% (SD 32.6), DIAM=44.6% (SD 25.1); $p=0.30$]. Patient-reported preoperative leg pain was significantly higher in the Micro group [66.9% (SD 29.5)] compared to the DIAM cases [48.0% (SD 27.8); $p<0.01$].

<u>Serial inter-group comparisons:</u> Improvement in function at 12 months postoperatively

compared to baseline values was better in the Micro cohort [37.2% RMQ; clinically important improvement (SD 25.6)], than in the DIAM cases [19.7% ODI; minimally clinically acceptable improvement (SD 26.7)]. Improvement in back pain at 12 months postoperatively compared to baseline values was not statistically different between both groups [Micro=39.1%; clinically important improvement (SD 36.0), DIAM=23.5%; minimally clinically acceptable improvement (SD 31.3); p=0.06]. Improvement in leg pain at 12 months postoperatively compared to baseline values was better in the Micro cohort [57.7% improvement (SD 32.3)] than in the DIAM cases [32.8% improvement (SD 33.8)]; both exceeded clinically important thresholds. Figure X.1 illustrates the baseline and serial comparison results for both groups. Mean (SD) values for all variables at each of the four time-points are outlined in Table X.1.

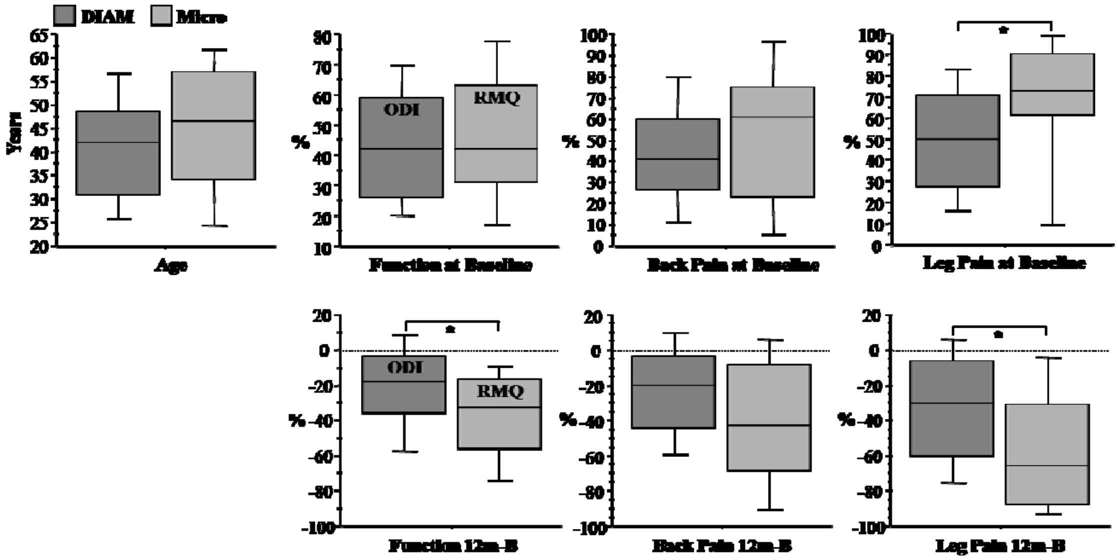

Figure X.1: Box-plots illustrating intergroup comparisons between: *Top set*: baseline ages, function, back and leg pains. The microdiscectomy (Micro; n=48) cases had significantly higher leg pain than the augmented-with-DIAM (n=29) cases [*p<0.05]; *Bottom set*: change scores between the 12 month postoperative and preoperative values. The microdiscectomy cases (n=48) had significantly greater improvement [p<0.01] in self-reported function and leg pain than the augmented-with-DIAM cases (n=29). Higher percentages indicate either poorer function or worst pain (baseline charts), and greater improvement (i.e. higher negative values) (year outcomes).

<u>Serial intra-group comparisons:</u> Serial results for both cohorts are illustrated in Figure X.2.

Microdiscectomy alone (Micro): Results for function, back pain and leg pain at all four time-points: baseline, 6 weeks, 6 months and 12 months postoperatively, are summarised in Table X.1 and Figure X.2. The 48 Micro cases exceeded clinically important (≥30%) improvement in the three self-reported questionnaire variables: function, back pain and leg pain, at all time-points compared to their preoperative state (p<0.01). Function, as determined with the RMQ, showed best reduction at one year by 37.2% (25.6). Back pain, as determined using a VAS, showed the best improvement (by 42%) at 6 weeks after surgery, which deteriorated mildly such that improvement at one year was 39% (36.0). Leg pain, as determined using a VAS, showed best improvement (by 59%) at 6 weeks, deteriorating mildly such that it was reduced at one year by 57.7% (32.3). All serial comparisons remained significantly improved (p<0.001) for each sub-set when split by gender [F (n=18); M (n=30); level of implantation: L3/4 (n=2), L4/5 (n=24), L5/S1 (n=22); and type of surgery [micro (n=34); micro+access (n=14)]. Three cases (of 48) required revision lumbar surgery at the same index level within the year of follow-up.

Table X.1: Mean (SD) values for function, back and leg pain self-reported outcomes after microdiscectomy augmented with the Device of Intervertebral Motion (DIAM; n=29), or microdiscectomy decompression (Micro; n-48) in treatment of a herniated nucleus pulposus and related sequelae.

		Baseline	Six w	Six m	Twelve m	12m-B	12m-B/B
F	DIAM	42.7 (19.1)	24.9 (19.6)	23.4 (25.9)	23.0 (24.1)	-19.7 (26.7)	-72.3 (41.4)
	Micro	45.8 (22.5)[1]	20.7 (15.2)	10.3 (13.3)	8.6 (13.5)	-37.2 (25.6)[2]	-86.1 (21.6)[1]
B	DIAM	44.6 (25.1)	18.6 (21.4)	26.2 (30.6)	21.1 (29.2)	-23.5 (31.3)	-59.3 (47.9)
	Micro	51.9 (32.6)[1]	9.4 (15.7)	11.0 (16.1)	12.8 (16.6)	-39.1 (36.0)[1]	-38.6 (96.4)[1]
L	DIAM	48.0 (27.8)	16.5 (25.3)	18.8 (29.2)	15.2 (23.6)	-32.8 (33.8)	-78.1 (39.7)
	Micro	66.9 (29.5)[2]	7.9 (15.8)	7.9 (15.8)	9.1 (18.3)	-57.7 (32.3)[2]	-89.2 (19.1)[1]

F=function; B=back pain; L=Leg pain; w=weeks; m=months; DIAM=cases who received lumbar microdiscectomy augmented with the DIAM interspinous implant; Micro=cases who received lumbar microdiscectomy surgery in treatment of HNP. Function was assessed using the Oswestry Disability Index for the DIAM group and Roland-Morris questionnaire for the Micro group. [1]No significant difference between DIAM and Micro groups.
[2]Significant difference between DIAM and Micro groups (p<0.01).

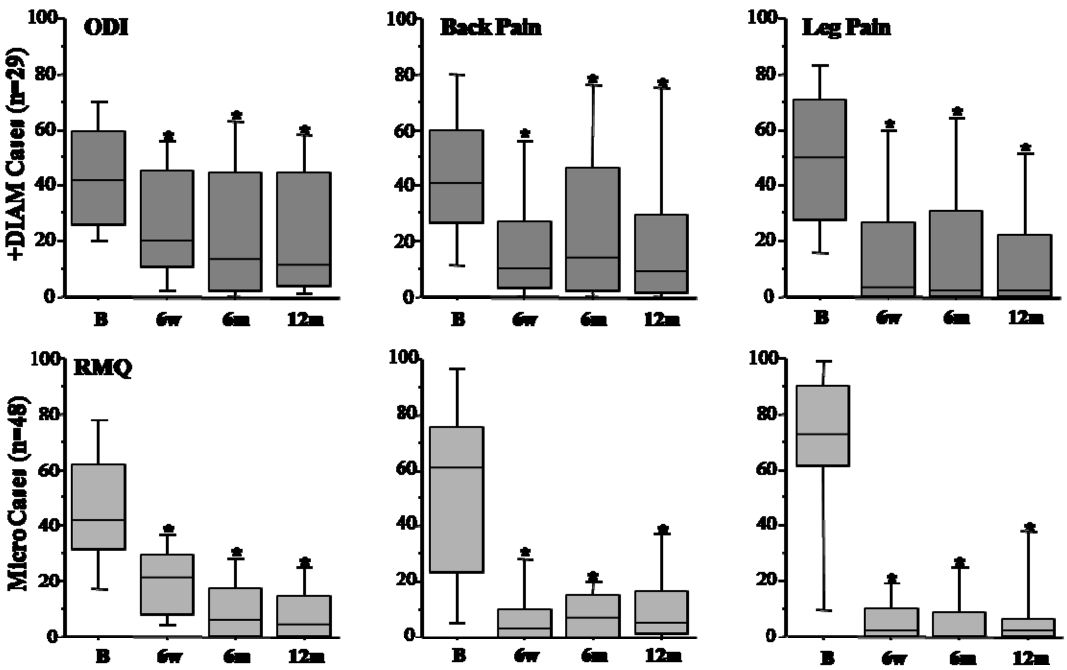

Figure X.2: Serial group results for two cohorts who received lumbar surgery in treatment of a single-level HNP: microdiscectomy alone (n=48) and microdiscectomy augmented with DIAM (n=29). Results indicate significant improvement at all time-points compared to baseline for both groups (*p<0.01).

DIAM-augmented disc decompression (DIAM): The 29 DIAM cases revealed statistically significant improvement in the three self-reported questionnaire variables: function, back pain and leg pain, at all time-points compared to their preoperative state (p<0.01) (Table X.1 and

Figures X.1&2). Function, as determined with the ODI, showed best reduction at one year by 19.7% (26.7). This represents minimally acceptable but not important clinical change. Back pain, as determined using a VAS, showed the best improvement (by 26%) at 6 weeks after surgery, which deteriorated mildly such that improvement at one year was 23.1% (31.3), representing minimally clinically acceptable change. Leg pain, as determined using a VAS, showed best improvement at one year by 32.8% (33.8), thereby exceeding clinically important change.

Figure X.3 illustrates year outcomes for the DIAM-augmented cases according to gender, clinical diagnosis, segmental level of surgery, and surgical decompressive technique(s) employed. When split by gender, the male cases (n=19) had improved function, back and leg pain at all time-points, while the female cases (n=10) had only improved function at 12 months compared to baseline. The seven cases who had a HNP in the presence of degenerative spondylolisthesis (DS) did not improve as a result of the surgery in terms of function or pain. The 22 subjects with HNP alone were significantly better at all time-points compared to baseline and for each assessed variable. Four cases (of 29) required revision lumbar surgery at the same index level within the year of follow-up.

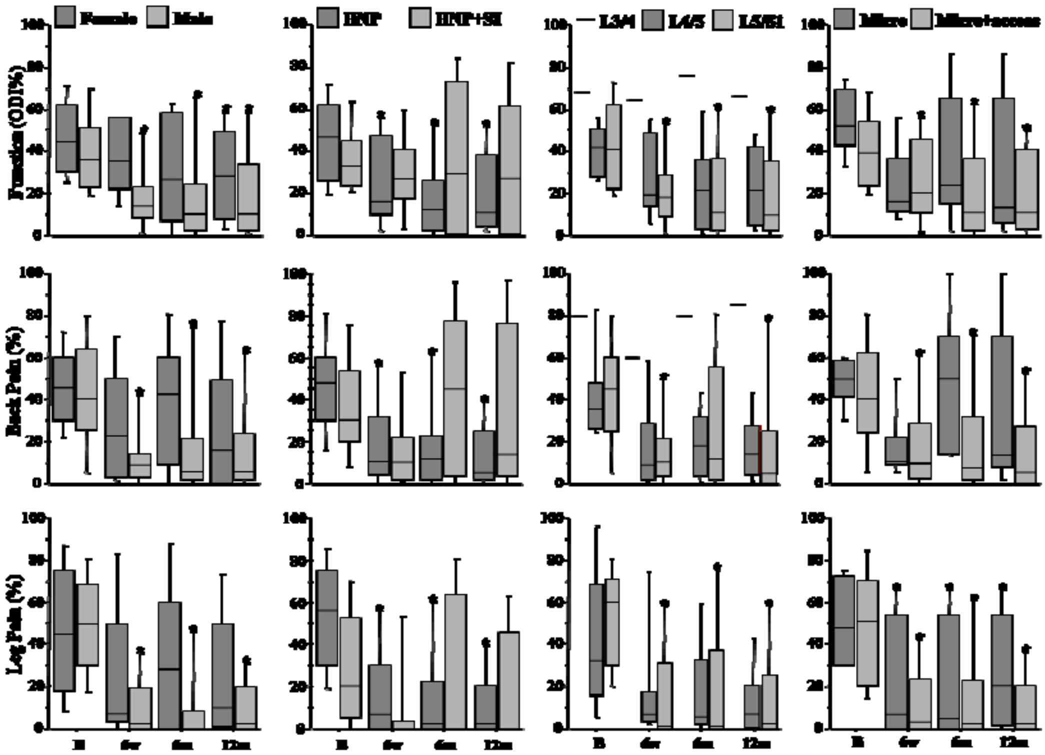

Figure X.3: Box-plots revealing serial change in function, back and leg pain for the DIAM-augmented cases (n=29) according to gender, clinical diagnosis, index level of surgery, and perioperative decompressive techniques employed in addition to implanting the DIAM. *indicates statistically significant difference compared to baseline values (p<0.01).

When considering the level of surgery, function and back pain were only improved in those receiving surgery at L5/S1 (n=20). Those with L4/5 (n=8) and L5/S1 surgery had improved leg pain compared to baseline. When serial data were split according to the surgery performed perioperatively, those cases receiving microdiscectomy alone and augmented with DIAM (n=5) did not describe improving function or back pain at any postoperative time-point, but were significantly better in terms of leg pain ($p<0.01$).

This compared with the cases receiving microdiscectomy in addition to an access surgical technique plus DIAM implantation [micro+access (n=24)] who were better at each time-point for all three variables. Four cases (of 29) required revision lumbar surgery at the same index level within the year of follow-up. This proportion represents double the number of cases needing repeat lumbar surgery than for the microdiscectomy group.

Discussion: Results of the present study showed that cases receiving microdiscectomy or microdiscectomy plus DIAM implantation in treatment of their HNP by the same neurosurgeon, all had statistically significant improvements compared to baseline, out to one year postoperatively. Minimal clinically significant change is reported to be >15% for function (via the RMQ or ODI) and >20% for pain as assessed with the VAS (Dworkin et al. 2008). Clinically important change is said to occur with improvements from baseline of 30% or more for all three variables used (Dworkin et al. 2008). Inspection of Table X.1 reveals that for each variable in both cohorts, minimally clinically significant change occurred, while clinically important change occurred in the Micro cases for all three variables, and only for leg pain in the DIAM-augmented group. This result indicates that microdiscectomy alone was more successful in those for whom it was selected as treatment of their HNP, than those who received the addition of a DIAM as well. Additionally, and in further support of this assertion, the proportion of repeat or revision lumbar surgeries for the Micro group (3/48) was less than in the DIAM group (4/29) over a similar time period. In combination, these findings do not support the hypothesis that the addition of a DIAM results in superior outcomes than for microdiscectomy alone when used to surgically treat HNP. This result appears in agreement with the study of Kim et al (2007) who showed that the adjunctive use of a DIAM with microdiscectomy (for HNP) or laminectomy (for LSS), did not improve pain or function at one year postoperatively more than the decompressive surgical procedure alone. It is difficult to draw conclusions based on the findings of the present study and that of Kim et al, as various limitations between and within both studies exist. Limitations of the present study are explored in more detail below.

Inspection of Figure X.1 reveals a marked difference in leg pain at baseline between both cohorts, which was significantly higher on average in the Micro patients (67% versus 48%; $p<0.01$). To be considered appropriate for DIAM-augmented surgery, the surgeon's clinical rationale (outlined in Chapter 3) generally required patients to have been symptomatic for more than 3 months, with failed conservative treatments within that period (Malone 2007). It can therefore be reasoned that the DIAM cases had reached chronicity of their lumbar spine problem. The same may not be as confidently said for the Micro cases. A careful review of the patient selection criteria for the relevant study did not outline the surgeon's patient selection process for microdiscectomy (Lynn 2009a). The higher pain presentation of the Micro group is suggestive of a more acute, medically unremitted, radicular (nerve root) irritation (Awad and Moskovich 2006), which may explain the disparity in preoperative leg pain between the two cohorts. Also of consideration is that microdiscectomy may be employed more often as a surgical treatment of HNP to alleviate leg pain in predominance to back pain (Awad and Moskovich 2006).

Given the Micro cohort had higher preoperative leg pain than the DIAM-augmented cohort, it is not unreasonable that a greater improvement in leg pain at one year compared to baseline was noted for the Micro cases (reduced by 58% versus 33%; $p<0.01$). This represents a limitation to reporting pain and function as an actual change in percentage, where those that report the highest disability preoperatively, are emphasised. For example, individuals whose preoperative presentation is within the lower percentages (0-30%), yet who have a complete recovery to zero (no pain or functional deficit), may be under-represented within the mean group change. When using the alternative method of reporting change (proportion of improvement as a function of the patient's baseline status; 12m-B/B) in this study, no differences between improvements for both groups were detected. When interpreted using this relative change score compared to baseline values, which may bias cases reporting low pain and function at baseline, patients in both groups exceeded clinically important improvements for all three variables (Table X.1). Leg pain and function improved most in both cohorts; by more than 70% and 80% in the DIAM and Micro groups, respectively. The DIAM group reported superior relative improvements in back pain (~60%) as compared with the Micro cases (~40%).

Patients assessed in the DIAM cohort represented a constellation of pathologies, surgeries, and symptoms that were grouped for convenience in this comparison study. The difference in group composition between the two cohorts therefore represents a limitation. Although the commonality of the group was their receiving microdiscectomy, the various laminotomy approaches involved different quantities of bone and soft tissue excision as considered necessary by the surgeon for each individual (refer to Figure 2.7 for illustrated differences in location and area of various laminotomies). The routine practise of the neurosurgeon (and probably common to all surgeons) was to notate this as 'laminotomy' on the patient's peri-operative record, without specifics as to the quantity and site of tissues excised.

It might be argued that this comparison study did not test comparable baseline groups given both cohorts were sourced from the same neurosurgeon whose clinical reasoning had deemed one set of patients as only needing microdiscectomy alone, while pathologies of the other group were thought to require the additional ISP surgery. Therefore, it may be speculated that both groups of patients represent different cohorts, which, intuitively at least based on the surgeon's reasoning, implies a distinction between the two. Despite the two groups being applied the same clinical decision making, surgical technique and pre- and postoperative management routines as a consequence of being from the same single neurosurgical practise, it may be speculated that tacit differences in the two patient groups (or the surgeon's clinical reasoning process) existed. The DIAM-augmented case series was later than the micro alone study and therefore the evolution of the DIAM into the clinical reasoning of the surgeon in the later study should be considered.

A potential influence on the superior actual results of the Micro cohort may have been the postoperative physiotherapy rehabilitation they received, which was the predominant focus of the associated thesis investigation (Lynn 2009a). In her thesis investigation, Lynn showed that the microdiscectomy cohort, who underwent a structured rehabilitation programme based on McKenzie principles (McKenzie and May 2003), had superior results, particularly with respect to back pain, when compared to a cohort for whom postoperative treatments were more randomly applied. The cases involved in both of the investigations compared in the present study were patients of the same surgeon, and as such it may be surmised were applied similar postoperative protocols. However, in a personal communication with the physiotherapist who treated both cohorts of patients on referral from the surgeon, it was explained that cases receiving DIAM-augmented surgery received physiotherapy postoperative exercises that aimed to progressively promote improved lumbar extension and return of their optimum lumbar lordosis (Lynn 2009c). The postoperative management for both groups of cases was similar given their HNP origin, but differences did exist (Lynn 2009c). This may explain the varied postoperative recovery between the Micro and DIAM cases compared in the present study.

Figure X.2 and Table X.1 demonstrate a heterogeneous postoperative behaviour of the DIAM-augmented cases where the spread of data from 6 weeks to one year after the surgery is wider than that seen for the Micro cases. Analysing the DIAM cohort via subset data, as included for four variables in Figure X.3, reveals potential influences on the patient-reported pain and function. An interesting result illustrated in Figure X.3 is the wide variability and apparent deterioration at six months seen for the five cases receiving DIAM-augmented surgery that were diagnosed with an element of degenerative spondylolisthesis. The main thesis investigation will provide an elaboration on this observation.

The RMQ and ODI are used to report function for the Micro and DIAM-augmented cohorts, respectively. While both of these instruments are well validated and clinically useful tools that are widely recommended for capturing information concerning back-specific function (Bombardier 2000), they are distinctly separate entities (Roland and Fairbank 2000). As such, the differences noted in function for the two cohorts assessed here, should be interpreted cautiously when comparing overall improvement. Recommendations describing MCID for each report the same minimum values for both (Dworkin et al. 2008); therefore their comparative use in this study appears reasonable.

When splitting the cohorts into subsets to better appreciate the results, the limited subject numbers left in some groups arguably weakened the strength of conclusions and the utility of this series in providing comparative data for other investigators.

Conclusions: Microdiscectomy and microdiscectomy augmented with DIAM surgery, used in treatment of HNP as performed by the same surgeon, resulted in statistically significant improvements in function, back and leg pain at one year postoperatively. Clinically important change to function, back and leg pain was achieved for the microdiscectomy cases and for leg pain in the DIAM-augmented cases when actual change was assessed. Microdiscectomy augmented with DIAM did not result in superior outcomes compared with microdiscectomy alone. Male cases responded more favourably to the DIAM-augmented surgery than females. Cases with HNP responded superiorly to those with degenerative spondylolisthesis. Patients receiving decompressive access in addition to microdiscectomy augmented with DIAM, responded better than those who did not.

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APPENDIX XI

Complications after surgery using the DIAM interspinous implant: a case study presenting device posterior displacement at L4/5

Introduction: Surgery using the silicone-based Device for Intervertebral Assisted Motion (DIAM; Medtronic, Memphis, USA) is reported to offer safe and effective improvements in pain and function in treating lumbar pathologies, without the risk of significant intra-, peri- or post-operative complications (Caserta et al. 2002; Schiavone and Pasquale 2003; Medtronic 2006; Taylor et al. 2007). Despite this claim, few clinical trials have detailed the prevalence or type of adverse events in using the DIAM in a clinical setting. Surgical technique guidelines (provided by the product distributor) list inflammatory reactions, permanent ligament injury, ligament rupture and prosthesis removal, as possible undesirable secondary effects of the surgery (Medtronic 2006). Early DIAM-based papers report no material-related complications (Taylor 2001; Caserta et al. 2002; Guizzardi et al. 2003; Schiavone and Pasquale 2003; Mariottini et al. 2005). Taylor et al (2007) offer the most comprehensive description to date, reporting adverse events seen after surgery with the DIAM (Taylor et al. 2007). Table XI.1 presents a summary of studies reporting complications after DIAM-inclusive surgery, including the adverse events noted in the present investigation. It was felt that an improved awareness of potential complications may benefit the definitions of clinical indications for lumbar surgeries using the device.

Table XI.1: Summary of six studies reporting lumbar complications or failure with surgery using the DIAM. Repeat surgery (DIAM revision or new procedure) at the original site of the DIAM implantation was defined as surgical failure. Numbers of cases per adverse event are indicated for the cohorts studied.

										Repeat Surgery	
Study	n	Time	EB	DT	Infect	Other	SP#	Disp	HNP	Redo	New
Present study	81	2y	0	2	NR	0	0	1	6	5	8
Hrabalek et al, 2009	68	1-3y	0	0	1	0	0	0	0	1	0
Silva et al, 2008	30	1y	NR	NR	NR	1	1	1	NR	NR	NR
Fabrizi et al, 2007	1250	7y	NR	NR	12	NR	7	NR	NR	NR	24
Kim et al, 2007	31	8 to 51m	0	0	1	2	3	0	4	NR	NR
Taylor et al, 2007	104	20m	14	1	0	1	0	0	2	5	1

Time=period of follow-up; EB=excessive bleeding; DT=dural tear; Infect=surgery-related infection; Other=subjective lump in back (Kim et al. 2007), removal of L5-S1 supraspinous ligament (Kim et al. 2007), reaction to implant (Silva et al. 2008); SP#=fractured spinous process (during implantation or subsequent removal); Disp=displaced device; HNP=herniated nucleus pulposus; Redo=repeat DIAM surgery; New=additional surgery at the index segment; NR=not reported

The most prevalent postoperative adverse event associated with DIAM surgery appears to be the requirement for revision surgery using the device, or further surgery at the index segment as a consequence of deteriorating symptoms (Tables 2.3 & 9.1). This appears to be the most common complication for all interspinous devices reported in the literature, where incidences between 2 and 28% of further lumbar surgery are reported (Crawford et al. 2009b). In relation to their 104 DIAM surgery cases, Taylor et al (2007) detailed that revision DIAM surgery was necessary for lumbar meningocele in two cases (at 1 week and 2 months postoperatively), one case of recurrent HNP (at 5 months), plus two cases with recurrent symptoms (after 1year). Their sixth repeat operation involved a laminoplasty with arthrectomy and foraminotomy secondary to persistent symptoms (11 months). Four of the revision DIAM surgeries in the present study were done before 6 months for recurrent HNP, and one between 6 and 12 months postoperatively for continued back and/or leg symptoms. One case had additional microdiscectomy at the index level for a reherniated NP. The two laminectomies, four ALIFs (anterior lumbar interbody fusion), and a single disc replacement were performed after the 12 month postoperative time-point for the original surgery, based on persistent and unremitting symptoms.

Taylor et al did not report subluxation or dislocation of the device as a complication in their 104 cases that were followed over 20 months. The present study examining 81 cases over two years, and that of Silva et al (2008) assessing 30 cases for one year, both described a single case of displacement of the DIAM (Table XI.1). The adverse event of device displacement therefore appears uncommon after DIAM surgeries, although it is acknowledged that only limited evidence supports this premise. In a paper detailing 8 patients (of 69) with postoperative complications after X-Stop surgery, Barbagallo et al (2009) list four cases with five dislocated implants (one case with two dislocated devices). They proposed the definition of a dislocated device be displacement outside the interspinous area, with displacement within the interspinous region being termed migration (Barbagallo et al. 2009). Each of their reported dislocations occurred at L4/5, with the double-dislocation occurring at L3/4 as well. All dislocations happened within 6 weeks postoperatively and were not related to trauma. All four cases were treated with revision X-Stop surgery, during which a ruptured or detached supraspinous ligament was noted (Barbagallo et al. 2009).

The single case of posterior DIAM device dislocation observed in the present series is detailed below based on the case notes held by her surgeon. This case study aims to demonstrate the behaviour of the patient's pain, function and surface spinal curvature for two years after her index surgery, and then her pain and function for a further 6 months after repeat surgery.

Case study: posterior displacement of DIAM at L4/5

<u>Pre-operative history:</u>

Fifty-three year old (at the time of index surgery in mid-2007) female with recurrent low back and associated right leg pain (S1) for five years prior to the index presentation. A previous MRI (October 2004) revealed focal discogenic degenerative change at L4/5 and L5/S1; multilevel facet joint arthropathy; and an L4/5 disc bulge with narrowed subarticular zones, more prominent on the left. No neural impingement was noted. The patient had undergone a L5/S1 microdiscectomy by a different surgeon two years earlier. Prior to her mid-2007 neurosurgical consultation, the patient had received various interventional non-surgical treatments including facet joint injections (FJI), nerve root sleeve (NRS) blocks and manual therapies (including physiotherapy and chiropractic). None of these had adequately relieved symptoms beyond the short term. The patient was referred for neurosurgical consultation for her unremitting central low back ache that was associated with left leg pain.

Index presentation:

The patient's pre-surgical MRI (March 2007; Figure XI.1A-C) highlighted bi-level (L4/5 and L5/S1) disc derangement and facet arthropathy that had worsened since the previous imaging (3 years earlier). No nerve root impingement or recurrent disc protrusion was identified. Evidence of an inflammatory process secondary to disc degeneration at the L5 and S1 vertebral bodies was noted. Discography (June 2007) revealed a significant L4/5 posterior anular tear and degenerated L5/S1 disc, with both levels provoking familiar left worse than right leg pain (L5/S1='typical and worst symptoms'). After only short-term respite from FJIs and NRS blocks between March and July 2007, the patient was scheduled for decompressive surgery to be augmented with two DIAMs (L4/5 and L5/S1). The patient was preoperatively categorised by the surgeon (according to the study guidelines outlined in Chapter 3) with 'mixed' degenerative segment disease, associated with left L5 and S1 nerve root compression, secondary to foraminal stenosis at L4/5 and L5/S1. Her preoperative VAS back (91%) and leg (76%) pain were high, and she reported fair back-related function (ODI; 40%) [Figure XI.2]. The patient was overweight (BMI=30), was a non-smoker, and her back problem was not subject to compensation.

DIAM-augmented surgery:

Surgery included decompressive laminotomy at L4/5, augmented with placement of two de-ligatured DIAMs, which were inserted at L5/S1 (categorised as her primary level; 8mm device used) and L4/5 (10mm). The surgery was performed according to the recommended technique (Medtronic 2006; Taylor et al. 2007). All peri-operative aspects were routine.

Postoperative course:

The patient's peri and immediate postoperative course was unremarkable. She underwent a six-week rehabilitation programme conforming to the surgeon's routine postoperative protocol. This commenced the day of surgery and comprised lumbar extension-restoring exercises based on McKenzie principles (McKenzie and May 2003). Exercises were individually tailored to suit the patient, and progressed by an experienced physiotherapist (Lynn 2009b).

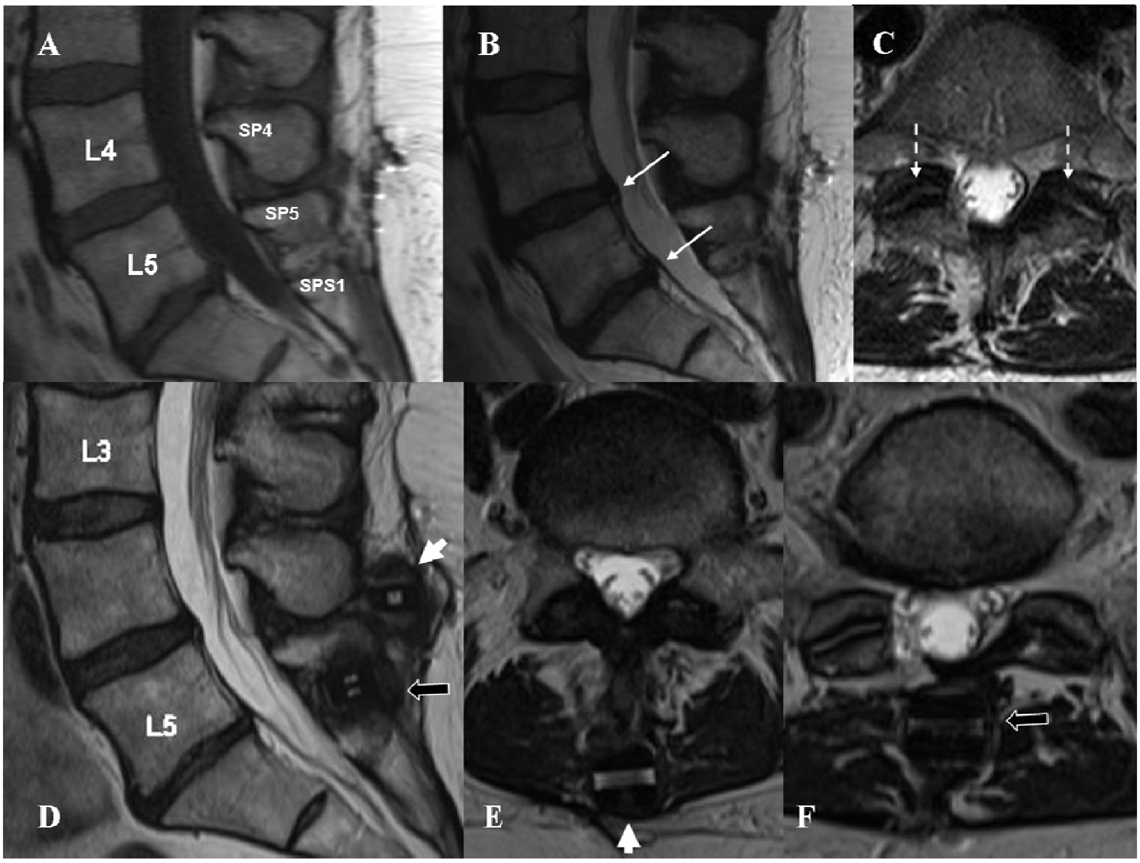

Figure XI.1: Preoperative (2007; top A-C) and 18 months postoperative (2009; bottom D-F) MR images for a 53 year old female who underwent decompressive laminotomy augmented with two DIAMs, in treatment of her bi-level disc (arrows in B) and facet degeneration (arrows in C for L5/S1) that were associated with left L5 and S1 nerve root irritation. Postoperative images taken at 18 months after surgery show a displaced DIAM at L4/5 (white arrow D&E) with the device at L5/S1 remaining interposed between the spinous processes (black arrows D&F). Displacement of the L4/5 device was insidious and not related to a traumatic incident. A ruptured supraspinous ligament at the level of the displaced implant was noted (anterior to the superior DIAM in image D).

As presented in Figure XI.2, the patient experienced dramatic improvement in her back and leg pain (VAS) and back-specific function (ODI) by the six week postoperative time-point, which further improved to 6 months. Thereafter, deterioration in back pain and function (by 12 months) preceded worsening leg pain (at 18 months). She received bilateral L4/5 FJIs at 7 months postoperatively, which allowed for an improved short-term tolerance to upright (extended) positions (patient report). At 13 months, the patient reported (to a physiotherapist) increased back, buttock and leg pain, which was associated with notably reduced active lumbar extension and tissue sensitivity surrounding the proximal sciatic nerve (as documented by the physiotherapist). Soft tissue manual techniques delivered by the physiotherapist, and associated home stretches, resulted in short term improvements in back and leg pain, and range of active extension. At 17 months postoperatively, the patient re-presented to physiotherapy with exacerbation of low lumbar and gluteal-region symptoms. After a brief episode of similar manual treatments, with limited benefit, she was subsequently referred back to the neurosurgeon via a pain specialist after receiving further (unsuccessful) FJIs at L4/5 and L5/S1, and an L5 NRS block. Repeat MRI at 18 months indicated the L4/5 DIAM to be posteriorly displaced, not interposed between the spinous processes (dislocated), and in the presence of a ruptured supraspinous ligament (Figure XI.1). No recalled incident or traumatic event related to the deterioration.

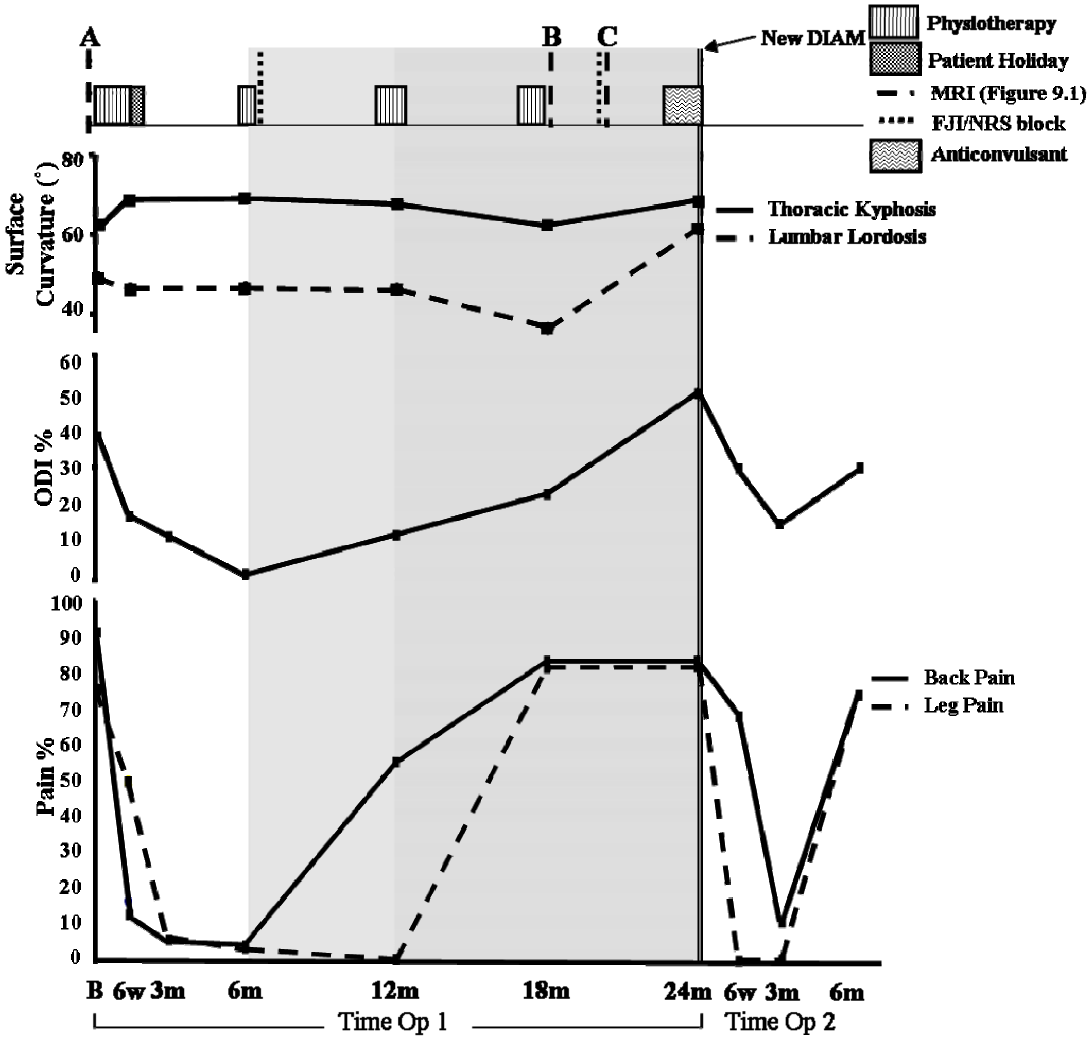

Figure XI.2: Initial two year self-reported pain (VAS; back and leg) and function (ODI), surface thoracic and lumbar curvature (measured via video rasterstereography), and non-surgical treatment intervention time-line for a 53 year old female who received lumbar surgery augmented with bi-level DIAM implants at L4/5 and L5/S1, in treatment of mixed segment lumbar pathology. Her first surgery was revised with removal of the L4/5 DIAM (that had become posteriorly displaced) and reinsertion of a new (one size larger) DIAM at the same level. Pain and function were followed for six months after the second surgery. Pain and function notably improved in the early postoperative period after both surgeries however, deterioration in symptoms occurred beyond 6 and 3 months after the first and second operations, respectively.

At 25 months, and after an unsatisfying six week trial of an anticonvulsant medication employed as a neuropathic pain modulator, the patient was readmitted for surgical removal of the displaced DIAM, which was replaced by another (12mm) at L4/5. Subsequent to the second surgery, the patient reported marked improvement in pain and function by 3 months postoperatively. Back and leg pain and function then deteriorated by the 6 month postoperative time-point. The subject's postoperative course has been presented schematically in Figure XI.2.

Discussion

This case study presents clinical outcomes of a 53 year old female with lumbar degenerative disc and facet disease, out to 31 months after her initial lumbar decompressive surgery augmented with two DIAM interspinous implants (at L4/5 and L5/S1). Without an associated traumatic incident, the 10mm DIAM implanted at L4/5 became posteriorly displaced, which was confirmed on MRI after the patient experienced deteriorating symptoms.

Although the dislocation was noted with imaging after her 18th postoperative month, inspection of the individual's outcomes data showed consecutive back and leg pain deterioration, by 12 and 18 months, respectively. It may therefore be speculated that device dislocation occurred somewhere between the six and 12 month period, thereby initiating her pain cascade, which commenced in her back. Figure XI.2 shows that change in back pain preceded pain described for the leg after the first surgery. Back pain improved before leg pain within the first six months postoperatively, to reach a minimal level at that time-point. Leg pain maintained improvement between six and 12 months, while back pain deteriorated markedly beyond six months out to two years post-operatively; leg pain had deteriorated by 18 months. This response suggests a peripheralisation (leg pain) of likely central (back pain) dysfunction relating to her disc and facet degeneration. The best effect of DIAM-augmented surgery for this female case appears to have been in the first 3 months after each of the DIAM surgeries presented, when notable improvement is shown for back and leg pain (VAS), and function (ODI). This is in agreement with the results presented for the whole prospective cohort in Chapter 7.1, and may represent a critical time-point.

In addition to the noted changes in pain and function, Figure XI.2 indicates that the most dramatic change to surface thoracic kyphosis and lumbar lordosis also occurred between her 12 and 18 month time-points, coinciding with deterioration in the patient's self-reported leg pain. Interactions between surface spinal curvature and responders to the surgery in terms of pain or function were reported in the previous chapter (8). These comparisons were assessed out to one year postoperatively and revealed no association at 12 months between surface posture and response to DIAM-augmented surgery in 27 cases. When change to LL (Figure 8.1) and TK (Figure 8.2) in the first 6 weeks postoperatively were considered, back pain improvement detected differences between responders and non-responders, while leg pain or function did not. It may be speculated that the lack of association relates to the timing of deterioration of leg pain, which appears to come after symptoms in the low back in this single case. This observation is made cautiously given the single case sample. Further investigation of surface curvature in relation to leg pain and function beyond 12 months postoperatively may therefore be of value.

However, Table 7.2.2 revealed no difference for 24 cases in mean values for any surface curvature variable at two years compared to baseline. Plus, while the line charts in Figure 7.2.1 indicate that a few cases had large changes to surface-derived LL, TK, PI and SB beyond the 12 month postoperative point, the clinical significance of these changes is questionable considering the lack of overall change, measurement error and normal postural variation.

Subluxation or dislocation of interspinous implants does not appear common, although only a limited literature exists to substantiate this for the DIAM (Table XI.1). Several studies describing outcomes after X-Stop surgery report infrequent cases of postoperative device displacement (Zuckerman et al. 2005; Anderson et al. 2006; Siddiqui et al. 2007; Barbagallo et al. 2009). Other than one DIAM case where details of displacement were not reported (Silva et al. 2008), the DIAM (present case) and four of the X-Stop displacements reported by Barbagallo et al, occurred at L4/5, with all being unrelated to trauma. Structural anatomy might implicate the lumbosacral interspinous space as the most likely site for displacement to occur, given the fixation and anchorage difficulties that a shallower first sacral spinous process may pose. However, a ruptured supraspinous ligament (SSL) was reported in the presence of each displaced ISP device, so the SSL preoperative integrity is of more relevance to the surgeon. The SSL and its associated thoracolumbar myofascial connections is arguably more developed at the lowest lumbar segment (Adams et al. 2002; Johnson and Zhang 2002; Vaccaro et al. 2009), which may speculatively explain why no identified reports describe ISP displacement at L5/S1. In the case of the DIAM, commentators may suggest that using its polyethylene fixing ligatures would mitigate any likelihood for displacement. These were not used in the surgeries for either the single case presented here, or the other 80 subjects in the main cohort. It is interesting that in the Fabrizi et al study that reported complications in a cohort comprising 1250 DIAM surgery cases followed over a 7 year period, no device displacements were reported. Their investigation was presented as a conference poster and not published elsewhere, and therefore study descriptions are limited (Fabrizi and Maina 2007).

In their recent investigation examining complications after X-Stop surgery, Barbagallo et al (2009) suggest that device migration or dislocation may relate to individual anatomy and the shape of the interspinous space in particular. They suggest that a V-shaped posterior interspinous area, as opposed to a parallel interspace, is not a suitable morphological feature for devices that are not fixed via clamps or ligatures (like the X-Stop or deligatured DIAM). Additionally, they suggest that short or poorly accessible spinous process length may also predispose to dislocation. Barbagallo et al list reduced interspinous distance and a convex or dysmorphic SP shape to represent potential risk factors for postoperative complications after ISP surgeries, particularly for SP fracture. Although the present series of 81 cases did not report this adverse event, Table XI.1 reveals three authors who did. It appears that patient selection criteria inclusive of individual anatomic features of the posterior column may be relevant in identifying clinical indications for the surgery. One case in the present series was intended for ISP surgery but was not implanted with a DIAM based on the surgeon's perioperative decision of anatomical insufficiency (and therefore was excluded from follow-up). Preoperative patient triaging with an anatomical basis (based on imaging) may be valuable in excluding inappropriate cases before they get to surgery.

The present study reported two cases (of 81) that were complicated by an intraoperative dural tear (DT), while Taylor et al (2007) listed one case with DT in their series of 104 patients treated with DIAM. The landmark SPORT (Spine Patient Outcomes Research Trial) studies describe a 4% incidence of DT in surgically-treated disc herniation (Weinstein et al. 2006), and an 8% incidence in the surgical treatment of spinal stenosis (Weinstein et al. 2008). The rate of DT in laminectomy patients is reported to be around 10%, with neurologic injury in about 2.5% (Malmivaara et al. 2007; Weinstein et al. 2008; Weinstein et al. 2009). A recent paper describing initial results from the Spine Tango registry, reported dural lesions as the most frequent intraoperative complication in the registry (Melloh et al. 2008). The rate of DT in DIAM surgery appears no worse than other decompressive procedures. Similarly, intraoperative excessive blood loss or infection is equivalently prevalent compared to rates reported for other decompressive surgeries (Weinstein et al. 2006; Weinstein et al. 2008; Weinstein et al. 2009). Controlled trials comparing decompressive surgery alone versus decompressive surgery augmented with ISP would be necessary to support this contention.

Conclusions

The potential for DIAM displacement at L4/5 is highlighted in this 53 year old female case. Back pain has the potential to precede leg pain as an indication of adverse centralised dysfunction in the case of a displaced DIAM. The preoperative integrity of the SSL may be relevant for surgeons considering the indication for surgery employing an ISP.

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APPENDIX XII

Data Summary: HRQoL, Rasterstereography, Radiography data available per case.

				Questionnaire							**Rasterstereography**						**Radiography**		
	Code	**Age**	**M/F**	**B**	**6w**	**3m**	**6m**	**12m**	**18m**	**24m**	**B**	**6w**	**6m**	**12m**	**18m**	**24m**	**B**	**6w**	**12m**
1	diam01	56	f																
2	diam02	39	m																
3	diam03	79	m																
4	diam04	24	f					R	R	R									
5	diam05	58	f																
6	diam06	57	f																
7	diam07	53	f																
8	diam08	47	m																
9	diam09	69	m					Lam	Lam	Lam				*	*	*			*
10	diam10	62	f																
11	diam11	53	f																
12	diam12	48	m				R	R	R	R									
13	diam13	58	f																
14	diam14	37	m																
15	diam15	59	m																
16	diam16	50	m																
17	diam17	44	f																
18	diam18	65	f																
19	diam19	56	m																
20	diam20	51	m																
21	diam21	31	m																
22	diam22	54	f																
23	diam23	57	f																
24	diam24	58	f																
25	diam25	55	f																
26	diam27	65	m																
27	diam28	68	f																
28	diam29	56	m																
29	diam30	46	m																
30	diam31	70	f																
31	diam32	62	m																
32	diam33	48	f																
33	diam34	66	f																
34	diam35	74	m																
35	diam36	20	m																
36	diam37	27	m						ADR	ADR					*	*			
37	diam38	55	f																
38	diam39	60	m																
39	diam41	48	m																
40	diam42	80	f																
41	diam43	44	f																
42	diam44	56	m																
43	diam45	42	f						ALIF	ALIF									
44	diam46	70	m																
45	diam47	60	m																
46	diam48	69	m							Lam						*			
47	diam49	57	m				R	R	R	R			*	*	*	*			*
48	diam50	47	m																
49	diam51	42	m						ALIF	ALIF					*	*			
50	diam53	37	m																
51	diam54	50	f						Micro	Micro									
52	diam55	45	f																
53	diam56	64	f																
54	diam57	70	m																
55	diam58	45	m																
56	diam59	50	f																
57	diam60	53	m																

58	diam61	62	m																
59	diam62	75	m																
60	diam63	56	f						ALIF	ALIF					*	*			
61	diam64	31	m				R	R	R	R			*	*	*	*			*
62	diam65	66	f																
63	diam66	25	f																
64	diam67	31	m																
65	diam68	57	m				R	R	R	R									*
66	diam70	59	f																
67	diam71	30	m																
68	diam72	25	m																
69	diam73	41	m																
70	diam74	41	f																
71	diam75	42	f																
72	diam76	42	f																
73	diam77	52	m																
74	diam78	48	m			R	R	R	R	R									*
75	diam79	31	m																
76	diam80	49	f							ALIF						*			
77	diam81	60	f																
78	diam82	55	f																
79	diam83	63	m																
80	diam84	53	f																
81	diam85	28	m																
		HRQoL available data																	
		Rasterstereography available data																	
		Radiography available data																	
		Both rastersteroegraphy and radiography available data																	
	R	Revision surgery with DIAM																	
	Lam	Further surgery=laminectomy																	
	ALIF	Further surgery=anterior lumbar intervertebral fusion																	
	ADR	Further surgery=Charite disc replacement																	
	Micro	Further surgery=microdiscectomy																	
	*	Excluded from assessment due to failed surgery																	