Equine Veterinary Journal

Equine Veterinary Journal ISSN 0425-1644
DOI: 10.1111/evj.12519

Water depth modifies back kinematics of horses during water treadmill exercise

K. J. NANKERVIS*, P. FINNEY and L. LAUNDER†

The Equine Therapy Centre, Hartpury College, Gloucestershire, UK
†Osteopathy for Horses, Welshpool, Powys, UK.

*Correspondence email: kathryn.nankervis@hartpury.ac.uk; Received: 31.10.14; Accepted: 12.10.15

Summary

Reasons for performing study: Water treadmill exercise can be incorporated into the rehabilitation programmes of horses recovering from back pathology, yet little is known about the effect of this type of exercise on thoracolumbar movement ranges.
Objectives: To measure the flexion-extension range of motion (FE ROM) of the thoracolumbar spine and pelvic vertical displacement during water treadmill walking at 3 water depths and compare these with the control condition.
Study design: Within-subject trial using a crossover design in healthy horses.
Methods: A total of 14 horses walked at 0.8 m/s on a water treadmill for 3 min at each of the following depths; hoof (control), metatarsophalangeal joint (low), tarsal joint (medium) and femoropatellar joint (high). Skin surface markers on T6, T10, T13, T18, L3, L5 and S3 were used to obtain FE ROM and the minimum and maximum angular motion pattern values (AMPmin and AMPmax) for T10, T13, T18, L3 and L5. Markers placed on left and right *tuber coxae* were used to obtain pelvic vertical displacement. Friedman's tests and *post hoc* Wilcoxon's signed ranks tests were used to determine the effects of water depth on measured variables.
Results: The FE ROM of T10 (8.4°), T13 (8.1°), T18 (6.9°) and L3 (6.4°) when walking at high depth was significantly greater than control (5.5, 5.7, 5.1 and 5.1°, respectively; $P<0.008$); T13 AMPmin was significantly lower in high water (−3.0°) than control (0.1°, $P = 0.001$) and L3 AMPmax significantly greater in high water (−1.9°) than control (−4.8°, $P = 0.001$). There was no significant association between pelvic vertical displacement and water depth.
Conclusions: Walking in high water causes cranial thoracic extension and thoracolumbar flexion when compared with walking in water at hoof depth. This postural change should be considered when designing rehabilitation programmes for horses with back and/or hindlimb pathology.

Keywords: horse; water treadmill; back kinematics; rehabilitation

Introduction

In recent years water treadmill exercise has increased in popularity within the training and rehabilitation of sport horses. It may be incorporated into an exercise programme with the aim of minimising concussion of distal limb joints [1], providing controlled, straight line exercise without the weight of a rider, promoting flexion of distal limb joints [2] or simply adding variety to the horse's work. Currently, the rationale for the use of water treadmills and exercise protocols employed vary according to the individual experiences of therapists and clinicians based on their own case results.

Some of the fundamental biomechanical characteristics of water treadmill exercise in horses can be predicted from a consideration of the drag force (F_D) acting on the limbs as they move through the water, given by the formula:

$$F_D = 1/2\,\rho A v^2\, C_D$$

Where ρ is the density of the water, v is the velocity of the object relative to the fluid, C_D is the drag coefficient (a dimensionless parameter) and A is the reference area [3]. Drag increases as a function of the velocity squared. The reference area A is the frontal plane of the horse which is submerged in water [3]. The density of the fluid and the drag coefficient are essentially constant for any given exercise session so the speed of the belt and the water depth are the major determinants of the drag force experienced by the horse walking in water. Water provides an upward thrust on the horse's body and limbs. The net effects of drag and buoyancy result in a relatively long stride duration [4], increased swing duration, reduced stance duration and greater flexion-extension ranges of motion of distal limb joints [2] compared with walking in water at hoof height at the same speed. As water treadmill exercise alters the pattern of movement of the limbs, an alteration in back kinematics could also be expected as limb and back movement are linked [5].

Evidence regarding the effect of water walking on the flexion-extension range of movement (FE ROM) of the thoracolumbar spine would be useful for practitioners considering how, or indeed whether, to incorporate this form of exercise within any given rehabilitation programme. The aim of this study was to measure the FE ROM of 5 regions of the thoracolumbar spine and also the pelvic vertical displacement during walking on a water treadmill at 4 water depths; hoof (control), metatarsophalangeal, tarsal and femoropatellar joints. Our hypotheses were that there would be an increase in FE ROM of the back with increasing water depth and an increase in pelvic vertical displacement with increasing water depth.

Materials and methods

Horses

A total of 14 competition horses of mixed breeds (11 Warmbloods, 2 Irish Sport Horses and one Thoroughbred) and discipline (5 dressage horses, 6 showjumpers and 3 eventers) aged 9 ± 4 years; weighing 600 ± 46 kg and 168 ± 5 cm in height were used. These horses formed a convenience sample selected from the regular client base of the Equine Therapy Centre, Hartpury College, which comprised horses undertaking water treadmill exercise once a week as part of their training programmes. All were believed to be sound and free from back pain according to their individual veterinary/therapy professionals. All horses were fully acclimated to the exercise and engaged in ridden work of up to 2 h 5 times per week. None were utilising the machine for the purposes of treatment of a known condition.

Experimental design and data collection: A within-subject trial using a crossover design was used. Horses were exercised in an Aqua-fit[a] water treadmill. Each horse carried out one exercise test which included a period of walking at 0.8 m/s at the following water depths; 'control' (hoof), 'low' (metatarsophalangeal joint); 'medium' (tarsal joint) and 'high' (femoropatellar joint). Seven horses exercised from control to high water within a single session and the other 7 worked from high to control depth to minimise any carryover of possible fatigue effects at any given water depth. Each horse carried out a 5 min warm-up at medium depth before either increasing to high water depth (n = 7) or decreasing to low (n = 7) to begin a stepwise exercise test of 3 min at each depth. Each exercise test lasted 17 min including warm-up. Four ProReflex opto-electronic cameras[b] sampling at 240 Hz were positioned around the water treadmill (1.5 m above the water treadmill). Reflective spheres[c] (19 mm diameter) were placed over the dorsal spinous processes corresponding to T6, T10, T13, T18, L3, L5, S3 and left and right *tuber coxae* for the purpose of measurement of FE ROM (in degrees [°]) (see Fig 1) and pelvic vertical displacement (in cm). Pelvic vertical displacement was used rather than pelvic axial rotation to enable comparison with previous work [6]. Data were collected for 20 s at each water depth for each horse. Individual strides were denoted by tapping a further reflective marker (stride marker) on the side of the water treadmill in time with the impact of the right hind hoof (noted audibly) since the solid sides of the treadmill prevented direct tracking of a hoof marker. Consecutive minima of the z trajectory of the stride marker corresponded to right hind hoof impact. This indirect method of determination of the start and end of each stride was compared with that using alternate minima of the z trajectory of the right *tuber coxa* in order to estimate the potential error introduced. For the purpose of this comparison 5 strides were selected from the mid-portion of the data for each horse at control and high water depths. The stride duration (in number of frames) using the right *tuber coxa* marker divided by the stride duration using the stride marker was 1.00 ± 0.01 in control depth water and 0.99 ± 0.02 in high water. The method was therefore deemed sufficiently accurate as a means of stride determination.

Data analysis

In the laboratory coordinate system, the positive y axis was along the line of progression, the positive z axis orientated upward and the x axis orientated perpendicular to the y and z axis. The x, y and z trajectories of each marker were filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 10 Hz. Data were separated into individual stride cycles using the stride marker as described above. All whole strides with 100% marker capture were used for analysis. This resulted in a minimum of 5 strides and a maximum of 12 strides available for each horse at each water depth. Angular motion patterns (AMPs) for T10, T13, T18, L3 and L5 were obtained for each stride using the method described previously whereby the instantaneous orientation of a vertebra (e.g. T10) was calculated from the position of the vertebrae cranial (T6) and caudal (T13) to the vertebra under scrutiny using the z and y trajectories of each vertebral marker [7]. The peak value from the AMP (AMPmax) from each stride was considered to be peak flexion and the minimum value (AMPmin) considered to be peak extension. The mean AMPmax–mean AMPmin of all strides at each location (T10 to L5) was used to calculate the FE ROM for each horse. Pelvic vertical displacement was determined by calculating the mean vertical displacement of the left and right *tuber coxae*.

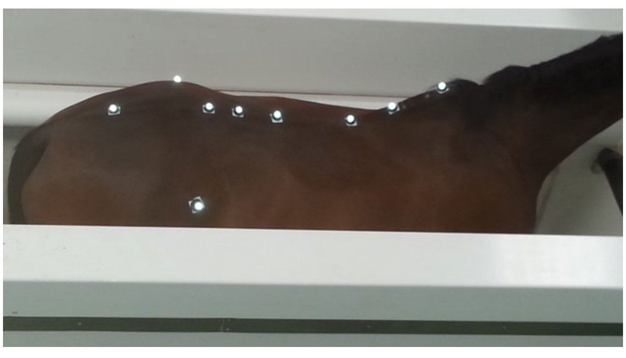

Fig 1: Horse in water treadmill showing the marker set used to measure thoracolumbar FE ROM and pelvic vertical displacement.

Statistical analysis

Statistical analysis was conducted using SPSS version 21.0 (Statistical Package for the Social Sciences [SPSS])[d]. The FE ROM, mean AMPmax and mean AMPmin for each back angle and pelvic vertical displacement were tested for normality using Shapiro–Wilks tests. In total, 31 of the 64 datasets tested were found to be not normally distributed. Nonparametric tests were therefore chosen and data are presented as group medians (95% CI). The between-stride variability in FE ROM was estimated using the coefficient of variation (CV) as follows: the standard deviation (s.d.) of the FE ROM for each individual horse (based on 5–12 strides) at each angle and each water depth was used to obtain a group mean s.d. The group mean s.d. was then divided by the group mean FE ROM × 100 to give a CV for each angle at each water depth. The CVs for each angle were then averaged to give a mean CV of variation for each water depth.

Associations between FE ROM, AMPmax, AMPmin, pelvic vertical displacement and water depth were tested for significance using a series of Friedman's tests (with significance level set at P<0.05) followed by *post hoc* analysis where significance was found. *Post hoc* analysis consisted of Wilcoxon's signed ranks tests with a Bonferroni correction applied, resulting in a significance level set at P<0.008 (i.e. P = 0.05/6; 6 being the number of *post hoc* comparisons). Following testing for normality, a series of Mann–Whitney *U* tests were used to check for differences in FE ROM, AMPmax, AMPmin and pelvic vertical displacement between horses that completed a stepwise test with decreasing water depth and those that completed a stepwise test with increasing water depth test using a significance level of P<0.05.

Results

Flexion-extension range of motion (FE ROM)

Group median FE ROM varied from 5.1° (for T18 and L3 in control depth water) to a maximum of 8.4° (T10 in high depth water) tending to increase with water depth (Table 1). The group mean CV of FE ROM at control, low, medium and high water was 22, 19, 18 and 19%, respectively. Data were missing for one horse for T10 in medium depth water. There was a statistically significant association between FE ROM and water depth for T10 (P<0.001); T13 (P<0.001); T18 (P<0.001) and L3 (P<0.001) but not for L5 (P = 0.4). *Post hoc* tests revealed significant increases in FE ROM between control and water walking for T10 (P = 0.001, 0.003 and 0.001 for control–low, control–medium and control–high, respectively), T13 and T18 (P = 0.001 for control–low, control–medium and control–high) and L3 (P = 0.004, P = 0.001 and P = 0.001 for control–low, control–medium and control–high, respectively). Flexion-extension range of motion for T13 was also significantly greater in medium depth than low water (P = 0.004).

Minimum angular motion pattern values (AMPmin)

Minimum angular motion pattern values varied from −10.5° (95% CI −13.3°, 7.8°) to 10.9° (95% CI −20.7°, 15.4°) (see Table 1). There was a statistically significant association between AMPmin and water depth for T10 (P<0.001); T13 (P<0.001) and T18 (P<0.001), but not for L3 (P = 0.074) or L5 (P = 0.405). *Post hoc* tests revealed a significantly lower AMPmin during water walking for T10 (P = 0.001, P = 0.004 for control–low and control-medium, respectively), T13 (P = 0.002, P = 0.003, and P = 0.001 for control–low, control–medium and control–high, respectively) and T18 (P = 0.004, P = 0.001 and P = 0.001 for control–low, control–medium and control–high, respectively). Minimum angular motion pattern values around T13 were also found to be significantly lower in high water compared with low water (P = 0.004).

Maximum angular motion pattern values (AMPmax)

Maximum angular motion pattern values varied from −4.8° (95% CI −8.1°, 12.8°) to 17.5° (95% CI −14.4°, 23.5°) (see Table 1). There was a statistically significant association between AMPmax and water depth for T10 (P = 0.033), T13 (P = 0.019), T18 (P<0.001), L3 (P<0.001) and L5 (P = 0.008). *Post hoc* tests revealed a significantly higher AMPmax

TABLE 1: Median flexion extension range of movement (FE ROM), minimum angular motion pattern value (AMPmin) and maximum angular motion pattern value (AMPmax) (95% CI) at control, low, medium and high water depths

	T10	T13	T18	L3	L5
ROM (°)					
Control	5.5 (4.5, 8.1)	5.7 (3.8, 8.0)	5.1 (3.6, 7.0)	5.1 (3.9, 7.0)	5.6 (4.7, 7.5)
Low	7.5 (5.2, 9.5)*	8.0 (4.8, 9.5)*	6.8 (4.3, 9.6)*	6.7 (4.8, 8.8)*	6.1 (4.8, 8.9)
Medium	7.7 (5.3, 9.9)*	8.0 (5.9, 10.7)*,†	7.1 (5.5, 10.7)*	7.0 (5.0, 11.1)*	6.0 (4.5, 9.7)
High	8.4 (5.7, 10.7)*	8.1 (6.2, 10.1)*	6.9 (5.9, 9.3)*	6.4 (5.5, 11.1)*	5.8 (4.7, 9.1)
AMPmin (°)					
Control	10.9 (−20.7, 15.4)	0.1 (−7.7, 8.3)	−7.7 (−11.5, 5.7)	−9.6 (−13.7, 8.6)	−2.9 (−5.8, −1.6)
Low	9.8 (−21.1, 14.4)*	−0.5 (−9.0, 2.1)*	−8.2 (−12.0, 5.2)*	−10.5 (−13.3, 7.8)	−2.2 (−5.1, −1.5)
Medium	8.8 (−21.2, 14.1)*	−1.7 (−8.5, 1.2)*	−8.1 (−12.8, 4.7)*	−10.2 (−13.6, 8.3)	−2.8 (−7.1, −2.3)
High	7.7 (−20.9, 15.1)	−3.0 (−9.3, 1.5)*,†	−8.4 (−12.4, 4.2)*	−9.6 (−14.0, 7.9)	−3.0 (−6.4, 2.2)
AMPmax (°)					
Control	16.0 (−15.1, 21.0)	5.2 (−1.2, 8.8)	−1.7 (−6.0, 9.6)	−4.8 (−8.1, 12.8)	2.5 (0.2, 7.1)
Low	16.8 (−14.1, 22.5)	5.7 (−0.9, 10.0)*	−1.0 (−5.3, 9.8)*	−2.9 (−7.4, 13.3)*	4.4 (0.9, 7.9)*
Medium	17.5 (−14.4, 23.5)	6.2 (−0.3, 10.4)	−0.4 (−4.9, 10.4)*	−2.7 (−4.5, 13.7)*	3.2 (−0.7, 8.1)
High	17.3 (−13.3, 23.6)	5.2 (−0.9, 8.9)	0.9 (−3.7, 10.3)*	−1.9 (−6.3, 13.7)*	3.6 (1.1, 7.9)

*Significantly different to control (P<0.008), †significantly different to low water (P<0.008).

compared with control for T13 (P = 0.005 for control–low), T18 (P = 0.005, P = 0.002, P = 0.001 for control–low, control–medium and control–high, respectively), L3 (P = 0.005, P = 0.002, P = 0.001 for control–low, control–medium and control–high, respectively) and L5 (P = 0.001 for control–low water).

Pelvic vertical displacement

Data were missing for one horse in high water. Pelvic vertical displacement was 6.5 cm (95% CI 5.8 cm, 8.3 cm) in control depth, 7.5 cm (95% CI 5.6 cm, 10.2 cm) in low water, 8.0 cm (95% CI 6.0 cm, 10.8 cm) in medium water and 8.5 cm (95% CI 5.5 cm, 10.6 cm) in high water. There was no statistically significant association between pelvic vertical displacement and water depth (P = 0.1).

The results of the Mann–Whitney *U* tests comparing FE ROM, AMPmax, AMPmin and pelvic displacement between horses that completed an increasing depth stepwise test and those that completed a decreasing depth stepwise test, showed that there were no significant differences resulting from the test type.

Discussion

Walking in water was associated with significantly greater FE ROM of all but the most caudal region (L5) when compared with walking at the control (hoof) depth thus supporting the hypothesis. Back movement is largely passive at the walk influenced by both limb movements and head and neck position [8]. An increase in FE ROM with water depth was expected as a result of the increase in stride length with increasing water depth [4].

Increases in FE ROM can be brought about by increases in flexion, extension or both. Comparison of the trends in AMPmax and AMPmin, particularly in the regions T13, T18 and L3, shows that increases in FE ROM are due to opposing changes within the thoracic and lumbar spine. The 13th thoracic vertebrae (T13) showed an increase in FE ROM in high water due to a decrease in AMPmin without a corresponding increase in AMPmax, reflecting a postural change towards increased extension in high water compared with low water. In low water the horse can lower the head and neck, which is known to cause cranial thoracic flexion [9]. Head position was not measured in this study but it is clear that in high water the horse is unable to lower the head much below the level of the scapulohumeral joint (in the case of this particular study) and given that most horses prefer to keep their head some distance above the water level the inability to lower the head may contribute to cranial thoracic extension.

In contrast to the pattern in T13, L3 showed an increase in FE ROM in water walking as a result of increased flexion (increased AMPmax). The 18th thoracic vertebrae (T18) sits between the 2 patterns demonstrated by T13 and L3 with both increases in flexion and extension in water walking. It was not possible in this study to measure simultaneous back and distal limb joint ranges but the latter have previously been studied [2] and can be used to explain the increase in both T18 and L3 flexion seen with increasing water depth. Greater distal limb joint ROMs (primarily because of increases in flexion) occur in all depths of water [2]. In accordance with the 'bow and string' model [10] increased flexion of hindlimb joints have the effect of 'tensioning the bow' via traction of the hindlimb retractors and epaxial musculature leading to the increases in peak flexion seen in this study. Previous study has shown that the greatest ROM of carpal joints occurs in medium depth water whereas the greatest ROM of the tarsal joint occurs in high water [2]. It follows then that the greatest thoracolumbar flexion would also occur at this depth.

In high water, caudal thoracic and lumbar flexion may also be assisted by the effect of buoyancy on the caudal trunk. Due to the 'pear shape' of the horse's trunk, there is a large increase in submerged surface area of the body on moving from tarsal to femoropatellar depth. The effect of buoyancy on the abdomen may assist flexion by simply opposing the downward pull of the abdominal weight on the lumbar spine. The assistance to flexion in the caudal thoracolumbar spine will no doubt have applications within the rehabilitation of certain conditions; however, the consequences more cranially should be taken into account, particularly if water treadmill walking is being considered within the rehabilitation of a horse with overriding dorsal spinous processes, which most often occur between T13 and T18 [11,12]. A primary treatment goal in the rehabilitation of these cases is the development of ROM in flexion within the affected region in order to widen the interspinous gap by strengthening and/or shortening the abdominal muscles to 'bend the bow' in accordance with the bow and string model of spinal stability. Exercise which promotes extension would therefore be contraindicated.

The FE ROM of L5 was largely unaltered by water walking, which at first sight seems at odds with an earlier study, where it was found that walking in water at all depths (from fetlock to shoulder) increased pelvic flexion compared with the baseline control condition of walking in water at hoof depth [6]. These authors used high speed videography to investigate the movement of the lumbar spine and pelvis during water treadmill walking in 12 riding horses. Measurement of pelvic flexion was obtained from a camera placed directly behind the treadmill to record the distance between the *tuber sacrale* and top of the tail. In the current study the only water depth resulting in a significant flexion of L5 compared with control was low water. The lack of change in FE ROM, AMPmax and AMPmin of L5, despite the changes in hindlimb movement in water treadmill walking [2,4], is perhaps not surprising given that the pivot point of the hindlimb during symmetrical gaits is the coxofemoral joint and not lumbosacral joint. The apparent lack of agreement with the earlier study [6] may simply be due to the fact that the 2 studies used very different methods to study back movement in this region.

This study utilised a 2D projection approach, the validity of which has been previously described [7]. A major assumption using this approach is that the horse's spine stays parallel to the y (craniocaudal) axis of the laboratory coordinate system. Using the 2D approach between-stride variability ranged from 5 to 10% in horses walking on a treadmill [7]. In this study, between stride variability in FE ROM ranged from 18 to 22%. However, the magnitude of the FE ROMs seen in high water in this study were comparable with those of horses walking on an ordinary treadmill at 1.6 m/s [13]. The walk speed used throughout the study of 0.8 m/s is approximately 50% of the typical walk speed for horses on a normal treadmill belt but was chosen because it is a comfortable speed for horses walking in water. While water walking was associated with increased FE ROM compared with walking at control depth at 0.8 m/s, it cannot be said that water treadmill walking increases spinal FE ROM over and above walking overland or on a treadmill at 1.4–1.6 m/s as a direct comparison was not made.

A study on the effect of a girth, saddle and weight on movements of the horse showed a 2° increase in extension of L3 and L5 between horses walking without and with a saddle plus 75 kg [14]. In the highest water depth used in this study the horse's back is effectively offloaded by approximately 10% (according to estimates [15]) and an increase in flexion (AMPmax) of L3 of approximately 3° were seen. Despite the large between-stride variability this change is therefore of a similar magnitude (albeit in a different direction) to a previous study [14]. It is not possible to predict the long-term impact of a relatively short (20 min) daily exercise session on the thoracolumbar posture of the horse but presumably the posture(s) adopted while walking in the water treadmill will be more influential the greater the proportion of water treadmill exercise within the total exercise programme, i.e. if water walking forms the only exercise carried out within a rehabilitation programme then the water depth chosen could influence the outcome of the case.

We found no significant association between pelvic vertical displacement and water depth and the second hypothesis was therefore rejected. This is in contrast to previous observations where a significant increase in pelvic axial rotation was seen during water walking (at any depth) compared with control [6]. The lack of significance in this study was due to the fact that only 6 out of 13 horses had the greatest pelvic vertical displacement in high water. The other 7 horses showed the greatest pelvic vertical displacement at medium depth (3/14), low depth (3/14) or control (1/14). This suggests that horses adopt different hindlimb movement strategies in response to water walking possibly due to differences in the strength of muscles activating the hindlimb, available joint range and/or low level lameness. None of the horses in the current study had any apparent lameness or back dysfunction and many were competing successfully in their chosen disciplines at an advanced level. However, given the potential for increased pelvic axial rotation during water walking seen in both studies, horses with hindlimb lameness and/or lumbopelvic pathology should be exercised with caution and their movement patterns carefully monitored for signs of fatigue such as marked asymmetry in pelvic axial rotation. With any rehabilitative exercise it is necessary to ensure the patient has the required range available to perform the movements and that intensity and volume is increased progressively in order to avoid fatigue.

Conclusions

Water walking increases the FE ROM of the thoracolumbar spine when compared with walking in water at the level of the hoof. There is a postural change towards mid-thoracic extension and thoracolumbar flexion. If the therapeutic goal is to promote thoracic flexion, walking in high water should be avoided. Further work is needed to determine the long-term effects of this form of exercise on spinal kinematics and associated spinal musculature.

Authors' declaration of interest

No competing interests have been declared.

Ethical animal research

The study was approved by the Hartpury College Research Ethics Committee. Owners gave informed consent for their horses' inclusion in the study.

Sources of funding

There were no external sources of funding.

Acknowledgements

The authors would like to thank L. Dumbell, Hartpury College for commenting on the statistical analysis and the staff of the Equine Therapy Centre, Hartpury College for support and assistance with this study.

Authorship

K.J. Nankervis conceived the study and carried out data collection along with P. Finney. L. Launder contributed to interpretation of the data and revision of the manuscript.

Manufacturers' addresses

[a]Herr Jung, Gesteut Nehmten, Germany.
[b]Qualisys Medical AB, Gothenburg, Sweden.
[c]B & L Engineering, Santa Ana, California, USA.
[d]IBM UK Ltd, Hampshire, UK.

References

1. King, M.R., Haussler, K.K., Kawcak, C.E., McIlwraith, C.W. and Reiser, R.F. (2013) Mechanisms of aquatic therapy and its potential use in managing equine osteoarthritis. *Equine Vet. Educ.* **25**, 204-209.
2. Mendez-Angulo, J.L., Firshman, A.F., Groschen, D.M., Kieffer, P.J. and Trumble, T.N. (2013) Effect of water depth on amount of flexion and extension of joints of the distal aspects of the limbs in healthy horses walking on an underwater treadmill. *Am. J. Vet. Res.* **74**, 557-566.
3. Alexander, R. (2003) Energy requirements for locomotion. *Principles of Animal Locomotion*, Princeton University Press, Oxford. pp 44-45.
4. Scott, R., Stringer, C., Nankervis, K., Westcott, K. and Marlin, D. (2010) The effect of water height on stride frequency, stride length and heart rate during water treadmill exercise. *Equine Vet. J.* **42**, *Suppl*. **38**, 523-529.
5. Van Weeren, P.R. (2009) Kinematics of the equine back. In: *Equine Back Pathology: Diagnosis and Treatment*, Ed: F.M.D. Henson, Wiley-Blackwell, Oxford. pp 41-42.
6. Mooij, M.J.W., Jans, W., den Heijer, G.J.L., de Pater, M. and Back, W. (2013) Biomechanical responses of the back of riding horses to water treadmill exercise. *Vet. J.* **198**, e120-e123.
7. Faber, M., Schamhardt, H., van Weeren, R. and Barneveld, A. (2001) Methodology and validity of assessing kinematics of the thoracolumbar vertebral column in horses on the basis of skin-fixated markers. *Am. J. Vet. Res.* **62**, 301-306.
8. Johnston, C., Holm, K., Faber, M., Erichsen, C., Eksell, P. and Drevemo, S. (2002) Effect of conformational aspects on the movement of the back. *Equine Vet. J.* **34**, *Suppl.* **34**, 314-318.
9. Denoix, J.-M. (1987) Kinematics of the thoracolumbar spine of the horse during dorsoventral movements: a preliminary report. In: *Proceedings of the 2nd International Conference on Equine Exercise Physiology*, Eds: Gillespie, J.R. and Robinson, N.E., ICEEP Publications, San Diego. pp 607-614.
10. Jeffcott, L.B. and Dalin, G. (1980) Natural rigidity of the horse's backbone. *Equine Vet. J.* **12**, 101-108.
11. Walmsley, J.P., Pettersson, H., Winberg, F. and McEvoy, F. (2002) Impingement of the dorsal spinous processes in two hundred and fifteen horses: case selection, surgical technique and results. *Equine Vet. J.* **34**, 23-28.

12. Erichsen, C., Eksell, P., Roethlisberger Holm, K., Lord, P. and Johnston, C. (2004) Relationship between scintigraphic and radiographic evaluations of spinous processes in the thoracolumbar spine in riding horses without clinical signs of back problems. *Equine Vet. J.* **36**, 458-465.
13. Faber, M., Johnston, C., van Weeren, P.R. and Barneveld, A. (2002) Repeatability of back kinematics in horses during treadmill locomotion. *Equine Vet. J.* **34**, 235-241.
14. de Cocq, P., van Weeren, P.R. and Back, W. (2004) Effects of girth, saddle and weight on movements of the horse. *Equine Vet. J.* **36**, 758-763.
15. McClintock, S.A., Hutchins, D.R. and Brownlow, M.A. (1987) Determination of weight reduction in horses in flotation tanks. *Equine Vet. J.* **19**, 70-71.