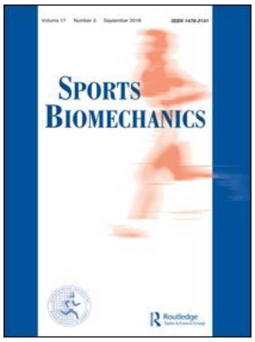

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Deceleration phase elbow varus moments: a potential injury mechanism for collegiate baseball pitchers

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ABSTRACT

The incidence of elbow injury experienced by baseball pitchers is on the rise. Biomechanical investigations focusing on the acceleration phase of the pitch have yet to elucidate a singular cause for these injuries. Leading to the question is there an additional significant stress on the elbow during other phases of the pitch? This study sought to determine the magnitude of the elbow varus moment during the deceleration phase of the pitching cycle for the fastball, curveball, slider and change-up. Eighty-seven collegiate-level pitchers were evaluated using motion analysis techniques to determine the magnitude of the elbow varus moment occurring during the deceleration phase. The results indicated that the elbow varus moment during the deceleration phase of the pitch was typically between 40% and 50% of the peak acceleration phase moment and was greatest when throwing a slider. Results also indicated that more pitchers experienced deceleration phase moments in excess of 50% of the acceleration moment when throwing breaking pitches. These moments which are the result of the pitchers' need to rapidly decelerate their arm produce an additional significant elbow varus moment that results in additional stress to the elbow.

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Kinetics; pitching; motion analysis; elbow

Introduction

Baseball pitching is a complex series of coordinated events that begins with the initial windup and ends with the pitcher getting into a fielding position. This motion places exceptional physical demands on the pitcher that may lead to injuries that could limit or end further pitching activities. It is well established that the incidence of shoulder and elbow pain experienced by pitchers is on the rise (Gugenheim, Stanley, Woods, & Tullos, 1976; Lyman, Fleisig, Andrews, & Osinski, 2002; Lyman et al., 2001; Mahure, Mollon, Shamah, Kwon, & Rokito, 2016) despite significant efforts to alter this increase. Researchers theorise that poor pitching mechanics, overuse and insufficient muscle strength and flexibility could all play a factor in pitching-related injury (Fleisig et al., 2006; Fortenbaugh, Fleisig, & Andrews, 2009; Nissen et al., 2009); however, biomechanical investigations have yet to elucidate a single cause for pitching-related injuries. It is

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also well established that the greatest stresses and fastest angular velocities experienced by pitchers occur during the acceleration phase of the pitch (Escamilla, Fleisig, Barrentine, Andrews, & Moorman, 2002; Fleisig, Andrews, Dillman, & Escamilla, 1995; Nissen et al., 2009; Solomito, Garibay, Õunpuu, Tate, & Nissen, 2013; Werner, Fleisig, Dillman, & Andrews, 1993). Given that the peak moments and velocities at the elbow and glenohumeral joint occur during the acceleration phase of the pitch, it is not surprising that nearly all of the pitching biomechanics literature has focused on this portion of the pitching cycle, while other phases have been largely ignored.

The deceleration phase, also known as the follow-through, begins after ball release. During this time, pitchers are required to abruptly stop their arm motion towards the plate and reverse their motion to get into fielding position after they have released the ball. During the deceleration phase, the muscles of the shoulder and elbow are acting eccentrically which has been reported to be associated with the injuries that occur during the deceleration of the pitch (Mikesky, Edwards, Wigglesworth, & Kunkel, 1995). Litchfield et al. reported that repetitive high-velocity throwing leads to micro-trauma in the upper extremity tendons and concluded that the mode of failure for these tendons was almost always during eccentric contraction of the muscles (Litchfield, Hawkins, Dillman, Atkins, & Hagerman, 1993). Therefore, it is important to determine the magnitude of a second elbow moment that occurs during the deceleration phase, as the presence of this moment could have a significant implication for injury risk.

Currently, only a handful of the early biomechanics papers describing the pitching motion discuss the deceleration phase of the pitching cycle (Escamilla et al., 2002; Fleisig et al., 1995; Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999). These papers only provide selected force and moment data for the shoulder and elbow between ball release and maximum internal rotation of the glenohumeral joint. Loftice, Fleisig, Zheng, and Andrews (2004) provided a measure of the elbow varus moment during this period and reported moments between 10 and 35 Nm (Loftice et al., 2004). However, none of these papers provide an in-depth analysis of this deceleration moment. Additionally, none of these papers have compared this late phase moment across different pitch types to determine if these eccentrically occurring moments may be a cause of the increasing injury incidence. Therefore, the purpose of this study was to determine the magnitude of the elbow varus moment which occurs during the deceleration phase across multiple pitching types. We hypothesised that breaking pitches (i.e., curveball and slider) and off-speed pitches (i.e., change-up) would have greater deceleration moments than the fastball.

Methods

This study was approved by the Connecticut Children's Medical Center's Institutional Review Board, and all study participants signed consent prior to the start of the pitching analysis. College-aged pitchers that pitched for either a National Collegiate Athletic Association (NCAA) Division I or Division III school were selected from a database of previously collected collegiate-level pitchers for this study. None of the participants involved in this study had sustained a serious injury or sustained an injury that caused them to miss pitching in at least one game or practice to their pitching arm within 6 months of the analysis. Additionally, none of the participants had a history of surgery to their pitching arm.

Data collection

Prior to starting the pitching analysis, anthropometric measures were taken to properly scale the inertial properties of the model. A total of 38 reflective markers were attached to specific anatomic landmarks to create a 16-segment biomechanical model as previously described by Nissen et al. (2007). An additional 2 markers were placed on the diameter of the ball to determine the instant of ball release, calculate ball velocity and allow for the computation of joint kinetics. It is known that the markers placed on the ball will slow the ball velocity between 5 and 7 mph (Solomito, Garibay, Golan, & Nissen, 2019). Therefore, all of the study participants were informed of this, and they received no feedback during the analysis about their ball velocity to ensure that they did not try to change their typical mechanics to gain additional ball speed.

Prior to the start of data collection, the participants were given as much time as they required to warm up and become comfortable pitching within the data collection space. All participants pitched from a 10-inch elevated mound towards a pitching target with a designated strike zone 60 feet 6 inches away. All participants pitched the pitch types (i.e., fastball, curveball, slider, cutter or change-up) that they felt most comfortable pitching in a game setting. The pitches were thrown in random order to simulate a game setting. Each participant pitched 7 of each pitch type that they had selected prior to data collection; all of the participants pitched between 21 and 28 pitches during the data collection. The data presented in this paper for the slider are a combination of both the slider and cutter as only a small handful of pitchers threw a cutter. Prior analysis between these 2 pitch types showed no statistically significant differences nor did it show any trends towards differences in kinematic or kinetic profiles, thus allowing for the data to be combined (Solomito et al., 2013). Motion data were collected at 250 Hz using a Vicon 512, 12-camera motion capture system (Vicon Motion Systems, Los Angeles, CA, USA). The first 3 trials for each pitch type in which all marker trajectories were present throughout the pitching cycle were analysed. These trials were picked regardless of the accuracy of the pitch to provide greater generalisability to the study results.

Data analysis

The pitching motion was divided into 5 phases, the first 4 phases are well described by Fleisig et al. (1995). The pitching cycle begins at the instant of lead foot contact with the mound (FC) and ends with the termination of the deceleration phase which is marked by the maximum internal rotation of the glenohumeral joint (MIR). The pitching cycle was further divided by 2 intermediate time points: the instant of maximum external rotation of the glenohumeral joint (MER) which marked the beginning of the acceleration phase of the pitching cycle and ball release (BR) which marks the end of the acceleration phase and start of the deceleration phase of the pitching cycle. In this work, an additional time point was included to mark the end of the deceleration phase and was determined by when the pedestal foot reached its highest point off the mound, and this time point was termed as maximum pedestal foot height (MFH). This time point was chosen as it was a repeatable and obvious point in the pitching cycle. Joint angles were computed using Euler's equations of motion using Vicon Workstation and BodyBuilder (Vicon Motion Systems, Los Angeles, CA, USA) as previously described (Nissen et al., 2007). All joint angles in this work are presented as a YXZ Euler rotation sequence with the only exception being the glenohumeral joint which uses an XYZ rotation. Joint kinetics were computed using custom MatLab code (MathWorks, Natick, MA) using standard inverse dynamic techniques (Greenwood, 1988). All kinetic data presented in this work are internal moments.

Data were computed for all joints for each participant over the entirety of the pitching cycle including the deceleration phase; however, data analysis was limited to specific variables of interest for this study, including the peak elbow varus moment during the acceleration phase of the pitching cycle and the peak elbow varus moment occurring during the deceleration phase of the pitching cycle. An additional value was computed for this study to describe the deceleration phase elbow varus moment as a percentage of the peak acceleration phase moment and is termed EVM%.

Statistical analysis

Descriptive statistics were computed for all variables of interest, and the means and SDs for continuous data are presented throughout this work. The calculated value of EVM% is a discrete variable, and as such, it is presented as count data. To further analyse the EVM%, the EVM% was divided into quartiles, and the number of pitchers within each quartile was counted. To determine if there was a significant difference in the distribution of EVM% by pitch type, a chi-squared analysis was used.

To determine the differences in the follow-up moments and the EVM%, a random intercept mixed-effects regression model capable of providing type III effects was used (Goldstein, Browne, & Rasbash, 2002; Greenland, 2000). This regression model was used because it is capable of taking into account repeated measures using all available trials, for this study 3 trials per pitch type, rather than using a single averaged trial or representative trial which increases the precision of the model by correctly accounting for variations in standard error and degrees of precision available. To determine differences in distributions for each pitch type when comparing the EVM% counts, a chi-squared test was used. All statistical testing was performed using SAS software 9.4 (Copyright$^{©}$ 2002–2010 by SAS Institute Inc., Cary, NC, USA).

Results

The results of this study were based on a total of 87 baseball pitchers with a minimum of 2 years of pitching experience and a mean age of 19.9 ± 1.4 years. All participants pitched a fastball, 78 pitched a curveball, 31 pitched a slider and 60 pitched a change-up. The average ball velocities for each of the pitch types are presented in Table 1.

The results of this study indicated that during the acceleration phase, the greatest peak elbow varus moments occurred in the fastball followed by the slider and curveball, and the lowest peak acceleration elbow varus moments were noted in the change-up (Table 2). However, the deceleration moments followed a very different pattern than the

Table 1. Comparison of ball velocity among the 4 pitch types.

Pitch type	Ball velocity (m/s)
Fastball (n = 87)	32.3 ± 2.3 [b]
Curveball (n = 78)	28.8 ± 2.7 [a]
Slider (n = 31)	30.3 ± 2.8 [ab]
Change-up (n = 60)	29.2 ± 1.6 [ac]

[a]Statistically significant compared to the fastball ($p < 0.01$).
[b]Statistically significant compared to the curveball ($p < 0.01$).
[c]Statistically significant compared to the slider ($p < 0.01$).

Table 2. Comparison of peak acceleration phase elbow varus moments among pitch types.

Pitch type	Acceleration phase peak elbow varus moment (Nm)
Fastball	75.9 ± 15.8
Curveball	70.6 ± 15.7 [a]
Slider	71.9 ± 15.6
Change-up	69.4 ± 15.1[a]

[a]Statistically significant compared to the fastball ($p < 0.01$).

well-established findings for the acceleration phase. The peak elbow varus moment occurring after MIR and prior to MFH was greatest for the slider with a moment of 34.4 ± 11.7 Nm, followed by the fastball and the change-up. The smallest deceleration phase peak elbow varus moment occurred for the curveball (Table 3). The deceleration phase peak elbow varus moment was significantly less in the curveball than in both the fastball and slider ($p = 0.002$ and $p = 0.003$, respectively).

The EVM% was between 42% and 48% of the acceleration phase peak elbow varus moment (Table 4). Interestingly, the slider and change-up had the largest EVM% compared to the fastball and curveball. These differences were statistically significant (Table 4).

The results of the distribution analysis indicated that the majority of pitchers had an EVM% below 50% when throwing the fastball, curveball and change-up; however, more than half of the pitchers throwing a slider had an EVM% greater than 50% (Table 5). Overall, 26% of pitchers pitching a fastball, 33% of pitchers throwing the curveball and

Table 3. Comparison of peak deceleration phase elbow varus moments among pitch types.

Pitch type	Deceleration phase peak elbow varus moment (Nm)
Fastball	32.8 ± 10.9 [b]
Curveball	29.7 ± 11.5 [a]
Slider	34.4 ± 11.7 [b]
Change-up	31.8 ± 8.5

[a]Statistically significant compared to the fastball ($p < 0.01$).
[b]Statistically significant compared to the curveball ($p < 0.01$).

Table 4. Comparison of peak deceleration phase elbow varus moments as a percent of the peak acceleration phase elbow varus moment among pitch types.

Pitch type	Peak deceleration phase elbow varus moment as a per cent of the peak acceleration phase elbow varus moment (%)
Fastball	44 ± 14
Curveball	42 ± 15
Slider	48 ± 13 [ab]
Change-up	47 ± 13 [ab]

[a]Statistically significant compared to the fastball ($p < 0.05$).
[b]Statistically significant compared to the curveball ($p < 0.01$).

Table 5. Distribution of pitchers based on pitch type and deceleration phase elbow varus moment as a percentage of the acceleration phase elbow varus moment.

	Distribution of pitchers			
Pitch type	EVM% < 25%	EVM% 25–50%	EVM% 51–75%	EVM% > 75%
Fastball	9	55	22	1
Curveball	5	48	23	2
Slider	1	13	14	3
Change-up	3	37	18	2

EVM%: deceleration phase elbow varus moment as a percentage of the acceleration phase moment.

change-up and 55% of pitchers throwing a slider had EVM% greater than 50%, and this distribution was statistically significant ($p = 0.0386$). Further analysis indicated that this finding was driven solely by the slider which had more pitchers with an EVM% greater than 50% than any of the other pitch types.

Discussion and implications

The purpose of this paper was to gain an understanding of the elbow varus moments that occur during the deceleration phase of the pitching cycle. Specifically, this study analysed how the deceleration phase moment differed based on the type of pitch thrown. Interest in determining this has stemmed from the unresolved dilemma that different pitch types may lead to pitchers experiencing a pitching-related injury. Biomechanical studies have pointed to the fastball, primarily due to its higher velocity, having higher medial elbow stress and therefore a presumably higher risk of injury. However, pitching coaches continue to believe that breaking pitches produce more arm stresses than the fastball (Dun, Loftice, Fleisig, Kingsley, & Andrews, 2008; Fleisig et al., 1995; Nissen et al., 2009; Solomito et al., 2013). The results of this study indicated that there is a substantial elbow varus moment that occurs after maximum internal rotation of the glenohumeral joint that is on average about 45% of the peak elbow varus moment typically analysed during the acceleration phase of the pitching cycle. The results also showed that the slider and change-up had the greatest deceleration phase elbow varus moments, and the slider had a greater number of pitchers with a deceleration peak elbow varus greater than 50% of the acceleration peak elbow varus moment.

The results of this work are consistent with the findings of Loftice et al. who indicated that the deceleration elbow varus moment was between 10 and 35 Nm

(Loftice et al., 2004). The results of this current work indicated that the average peak elbow varus occurring during the deceleration phase was closer to the higher end of this range (average across all pitches 32.2 ± 10.7 Nm). A potential reason for this skew in the data could be that Loftice et al. analysed only the period of the pitching cycle between ball release and MIR. In this current study, the deceleration phase beyond MIR was analysed to more accurately assess the follow-through period of the pitch. This decision was driven by early analyses that showed the presence of a second elbow varus moment typically occurring around 94–98% of the pitching cycle. To ensure that the analysis did not miss a peak occurring later in the follow-through phase, the timing of the pitching cycle was greatly expanded allowing for this second moment to be shown in its entirety.

When analysing the deceleration moment as a percentage of the acceleration moment, it was noted to be typically about 40–50% of the acceleration moment. As an absolute value, this moment that is on average less than half of the peak elbow varus moment typically reported in pitching biomechanics may seem trivial. However, there are 2 important factors to consider when interpreting this finding. The first concerns loading cycles on the pitching arm and the second concerns the fact that during the deceleration phase these moments occur during eccentric contractions of the muscles rather than concentric (Mikesky et al., 1995). From a purely mechanical standpoint, the presence of a second significant elbow moment occurring during the deceleration phase increases the cumulative loading factor on the soft tissue surrounding the elbow. In other words, if the pitch counts currently in place to protect pitchers from injury were based on a load factor that only accounted for stresses during the acceleration phase of the pitch, then these pitch counts may need to be revisited to include a consideration of the loading on the soft tissue structures during the deceleration phase. Additional research should be directed to this topic to better understand the implication of multiple soft tissue loading events during a single pitch, as the additional deceleration moment could be a potential source of injury as it is exposing the elbow to a second stress during the same loading cycle (i.e., the pitch).

The deceleration moment occurs when the muscles in the arm are acting eccentrically to slow and reverse the forward motion of the pitchers' arm to allow the pitcher to get into a fielding position. Eccentric contractions have been noted to be more associated with pain and soreness than concentric contractions (Newham, Mills, Quigley, & Edwards, 1983). In a study by Newham et al. looking at differences in pain during eccentric and concentric contractions, they found that eccentric contraction created a situation in which fewer muscle fibres were recruited but produced greater forces than concentric contractions, thereby increasing the risk of physical damage in the muscle and its attachments (Newham et al., 1983). Their study also showed that the pain and soreness were not localised to the muscle belly but rather in the areas of the musculotendinous attachments (Newham et al., 1983). Extrapolating from Newham et al., when the deceleration moment occurs, the muscles surrounding the elbow and shoulder are working eccentrically; therefore, even though the deceleration moment is about 50% of the acceleration phase moment, the magnitude of this deceleration moment may be large enough to cause soft tissue discomfort. During the deceleration phase, the elbow is in less flexion (less than 30° of flexion) than during the acceleration phase (around 80° of flexion) (Solomito et al., 2019). When the elbow is in a greater degree of extension, the bony congruency of the joint improves which in turn protects the UCL. Morrey and An (1983) indicated that, when extended, 69% of the varus moment is carried by soft tissue and the osseous articulation, while only 31% of the moment is carried by the UCL (Morrey & An, 1983). Therefore, the deceleration moment may cause pitchers a greater amount of soft tissue discomfort rather than causing direct injury to the UCL.

Additionally, of note were the results concerning the distribution of pitchers with deceleration phase elbow varus moments in excess of 50% of their acceleration phase elbow varus moment. There were a greater number of pitchers with EVM% in excess of 50% in both of the breaking pitches studied and the change-up (off-speed pitch) than the fastball. This may be the biomechanical reason to the statement often made by pitchers and coaches that breaking pitches produce greater stresses on the arm. Perhaps, this statement, ‘greater stresses’, is not referring to the actual stress but rather the associated pain and soreness that comes after pitching a number of varied pitch types.

This study is not without limitations. First, this is a laboratory study, and the effects of pitching in the controlled conditions of a lab may affect participant performance. However, this level of analysis is not currently viable in the field and is comparable to other motion-based studies currently in the literature. To simulate actual pitching conditions, we used a regulation mound, a full-length pitching space, and allowed participants time to warm up and feel comfortable pitching in a laboratory environment. Another limitation of this study is that the markers placed on the ball during data collection slow the pitch, resulting in a cohort average velocity lower than typically reported in the literature. However, all pitchers pitch with the same instrumented ball, and therefore, the reduced ball velocity is consistent across all study participants. This study explores only one small aspect of a portion of the pitching cycle that has not been thoroughly investigated previously. Therefore, it does not present timing or kinematic differences between pitching types that may produce additional understanding for these deceleration phase elbow varus moments, which should be a focus of future work. Finally, the data presented in this work are based on 87 collegiate-level pitchers; therefore, the results of this work may not be able to be extracted to younger ages or to professional-level athletes.

Conclusion

The majority of pitching biomechanics research focuses on the acceleration phase of the pitching cycle because the greatest angular velocities and joint moments occur during this portion of the pitch. This study presents joint moment data for the deceleration portion of the pitch. The results indicate that the elbow varus moments occurring during the deceleration phase were between 40% and 50% of the magnitude of the peak acceleration phase elbow varus moment. This additional moment occurs at a time when the upper arm muscles are acting eccentrically and may be a potential source of injury for baseball pitchers, as well as providing a possible explanation as to why pitchers believe that breaking and off-speed pitches may be more harmful than the fastball.

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