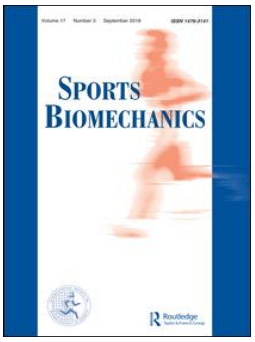

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The influence of trunk mechanics on the assessment of elbow position in college aged pitchers

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ABSTRACT

Researchers have postulated that the rise in the incidence of pitching injuries is partially due to poor pitching mechanics. A topic that is often debated revolves around the correct positioning of the elbow in relationship to the body. Therefore, this study attempts to understand the associations of vertical or horizontal elbow positon with upper extremity joint moments, and ball velocity, and how elbow position is influenced by trunk position. Motion analysis data from 99 collegiate pitchers were analysed for this study. A random intercept, mixed-effects regression model was used to determine if statistically significant associations existed between elbow position and upper extremity joint moments and ball velocity. Results indicated that visual impressions of the elbow position were highly correlated with trunk position, whereas kinematic definitions of elbow position were correlated to the glenohumeral angle. Visual vertical and horizontal elbow position was associated with increased elbow varus moments ($p = 0.001$) and ball velocity ($p = 0.019$), respectively. Whereas kinematic elbow position was not associated with either upper extremity joint moments or ball velocity. Therefore, what coaches visually interpret as an improperly positioned elbow may actually be a combination of lateral lean, anterior tilt, and over rotation of the trunk.

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KEYWORDS
Elbow position; trunk; kinetics; pitching

Introduction

The incidence of shoulder and elbow injuries in baseball pitchers has increased over the last few decades (Conte et al., 2016; Gugenheim et al., 1976; Lyman et al., 2001; Saper et al., 2018), and recent reports have indicated that the number of UCL injuries for baseball pitchers between the ages of 15 and 24 is expected to rise through 2025 (Mahure et al., 2016). Many researchers have postulated that this rise in the incidence of pitching injuries is partially due to poor pitching mechanics (Aguinaldo & Chambers, 2009; Chalmers et al., 2017; Fleisig et al., 1995; 2006; Nissen et al., 2009; Solomito et al., 2013; Werner et al., 2002). A topic that is often debated revolves around the correct positioning of the elbow during the pitching cycle. It has been described that when the upper arm is in 90° of vertical shoulder abduction (i.e., the elbow is at the level of the shoulder) and 0° of horizontal shoulder abduction (the elbow is in the plane of the trunk/body) the pitcher is in the 'power

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position' (Christoffer et al., 2019). When the arm is not in this slot studies have indicated that the there is an increased stress on the pitchers arm as well as a reduction in ball velocity (House, 2000). This theory has been explored to some extent (Escamilla et al., 2018), but the optimal arm slot that would allow pitchers to achieve the best performance with the smallest joint moments is still unclear.

Albright et al. were the first to compare visual assessment of the pitching motion with motion analysis data collected using slow motion video captured from multiple angles (Albright et al., 1978). Albright et al. determined that 'rushing the pitch' or 'opening up too early', essentially allowing the body to move or rotate in front of the pitching arm, increased the risk of injury for a pitcher (Albright et al., 1978). More recently, Werner et al. studied the pitching mechanics of 40 professional pitchers in a game setting and found several kinematic variables, including shoulder abduction angle at foot contact, were correlated with the elbow varus moment (Werner et al., 2002). However, a laboratory-based study conducted by Matsuo et al. contradicted Werner et al. when they found no evidence of a relationship between shoulder joint abduction and elbow moments in a cohort of 33 college pitchers (Matsuo et al., 2006). Simulation techniques have also been used to investigate the relationships between shoulder kinematics and elbow moments, and have determined that 90° of shoulder abduction position did not always minimise the elbow varus moment (Matsuo et al., 2002). Matsuo et al. evaluated the relationship between the elbow varus moment, shoulder abduction, and trunk lean (Matsuo et al., 2006). They determined that peak elbow varus moment was minimised at 100° of shoulder abduction and 10° of contralateral trunk lean. Their results, however, indicated that shoulder abduction alone had no significant relationship with elbow varus moments or wrist velocity. Hence, Matsuo et al. and others have proposed that further study is necessary to determine the contributing kinematic factors that affect elbow loads (Fleisig, 1994; Kamineni et al., 2004; Levin et al., 2004).

The pitching motion is complex and involves the movement of multiple joints in all three anatomic planes in a coordinated and precisely timed fashion. Therefore, determining whether or not a pitcher achieves an appropriate arm slot from visual assessment alone can be extremely difficult (Christoffer et al., 2019). Typically, coaches rely on visual qualitative assessments of a pitcher's mechanics while throwing from the mound (Escamilla et al., 2018). In many cases, coaches assess arm position using visual means, or use linear measurements using video analysis software (i.e., Dartfish (Dartfish, Fribourg, Switzerland)). Using these linear measurement methods, the vertical position of the elbow, elbow height, is assessed as the vertical distance between the shoulder and the elbow when viewed in the front (i.e., coronal plane). Similarly, the elbows horizontal position, elbow drag, is assessed as the horizontal distance between the shoulder and the elbow when viewed from the side (i.e., sagittal plane). What a coach visually assesses as a properly positioned elbow may actually be a combination of abnormal kinematic motions which, when summed, appear normal. For example, increased trunk lateral lean away from the pitching arm and decreased glenohumeral abduction can give the appearance that the pitchers' arm is in the appropriate slot when visually assessed. This misinterpretation is potentially dangerous for pitchers as previous studies have indicated that lateral trunk lean away from the pitching arm increases the elbow varus moment (Oyama et al., 2013; Fleisig et al., 2011; Solomito et al., 2015). This points out that visual assessment may not be able to fully appreciate the kinematic relationships between the elbow position, shoulder angle, and trunk position.

Therefore, the purpose of this study was to determine the difference between assessing elbow position in isolation compared to an assessment of elbow position taking into account the orientation of the trunk. It was hypothesised that the assessment of elbow position in isolation would be significantly associated with the position of the trunk, as well as the glenohumeral internal rotation moment, the elbow varus moment, and ball velocity.

Methods

This study was approved by Connecticut Children's Medical Centre's Institutional Review Board, and all study participants provided written consent prior to data collection. Ninety-nine college-aged pitchers were recruited for this study and their data were combined with other previously collected college-aged pitchers. All participants pitched for a competitive collegiate baseball team (i.e., National Collegiate Athletic Association Division I and III schools) and were between the ages of 18 and 24 at the time of data collection. None of the participants had previous shoulder or elbow surgery. Participants were also excluded if they had experienced a serious injury to their pitching arm, defined as an injury or pain that caused the participant to miss at least one game or practice in the preceding 6 months. At the time of the analysis, all participants denied shoulder and/or elbow pain and all were capable of pitching at full effort.

Anthropometric measurements (Table 1) were taken for each participant prior to the application of 38, 14 mm diameter reflective markers, which were attached over specific bony landmarks to allow the calculation of joint kinematics throughout the pitching cycle as previously described (Nissen et al., 2007). Two additional markers were placed on the ball in order to determine the time of ball release, calculate ball speed, and compute the upper extremity joint kinetics.

Prior to the start of the data collection, each participant was provided as much time as he required to warm up and feel comfortable pitching in the laboratory environment. All participants pitched from a regulation 10-inch mound towards a target with a designated strike zone located 60 feet 6 inches away. All participants pitched multiple pitch types (i.e., fastball, curveball, slider, cutter, or change-up) that they chose prior to data collection based on their comfort to throw those pitches in a game setting. All pitches were thrown in random order to better simulate a game experience. Each pitcher threw seven pitches of each of their pitch types resulting in a total of 21 to 28 pitches per participant. The results of this work are limited to an analysis of the fastball pitches only. Motion data were collected at 250 Hz using a Vicon 512, 12-camera motion system (Vicon Motion Systems, Los Angeles, CA, USA). For each participant, the first three fastball trials in which all reflective markers were visible throughout the pitch cycle were analysed, regardless of whether the pitch resulted in a strike or ball, as this allows the data to be

Table 1. Demographic data for the study cohort (N = 99).

Age (years)	19.9 ± 1.4
Height (m)	1.8 ± 0.1
Weight (kg)	88.8 ± 10.9
Upper arm length (cm)	34.4 ± 1.1

more reflective of a game setting. Pitchers were placed on the pitching mound near the lab origin and pitched in the negative x-direction, with the positive y-axis defined to the pitcher's right.

Initial data processing was performed using Workstation software (Vicon Motion Systems, Los Angeles, CA, USA) for marker reconstruction, creation of marker trajectories, and generation of kinematics using a 16-segment biomechanical model previously described (Nissen et al., 2007). A fourth-order zero-lag Butterworth filter with a 15 Hz cut-off frequency was used to smooth all marker trajectories. Joint kinetics were computed utilising custom MatLab code (MathWorks, Natick, MA, USA) based on standard inverse dynamics techniques (Greenwood, 1988). All moments presented in this work are internal moments. The pitching motion was divided by four event times as previously described (Fleisig et al., 1995), beginning with the instant of lead foot contact (FC) and ending with the instant of maximum internal rotation of the glenohumeral joint (MIR). The two intermediate events were the instant of maximal external rotation of the glenohumeral joint (MER) and ball release (BR).

For the purposes of this study, elbow vertical and horizontal positioning were calculated using two methods. The first method attempted to define the elbow position in isolation which would be analogous to a coaches visual assessment of elbow position and these variables were termed visual elbow vertical position and visual elbow horizontal position (Christoffer et al., 2019; House, 2000; House et al., 2006; House & Thorburn, 2008; Oyama, 2012). The visual methods of evaluation were chosen to most closely match the data that would be assessed either visually or through the linear measures made using computer-assisted video-based measures, as determined by conversations with coaching staff. The second method was based on a kinematic description of the elbow's position that accounted for trunk position; these variables were termed kinematic elbow vertical position and kinematic elbow horizontal position.

Visual elbow vertical position (Figure 1(a)) was assessed from the frontal view of the pitcher (i.e., from behind home plate) and was calculated as the vertical distance between the elbow joint centre and the glenohumeral joint centre in the y-z plane of the laboratory coordinate system. Similarly, visual elbow horizontal position (Figure 2(a)) was assessed from the side view of the pitcher (i.e., from third base for a right-handed pitcher or from first base for a left-handed pitcher) and was calculated as the horizontal distance between the elbow joint centre and the glenohumeral joint centre in the x-z plane of the laboratory coordinate system. It is important to note that although these measures are termed as 'visual' the results are calculated using motion analysis data in a laboratory coordinate system.

Kinematic elbow vertical and horizontal positions (Figures 1(b) and 2(b)) evaluated kinematic variables evaluate the elbow's position in relation to the pitcher's shoulder girdle and trunk. Kinematic elbow vertical position was calculated as the vertical distance between the elbow joint centre and a vector extending through the right and left shoulder joint centres. Similarly, kinematic elbow horizontal position was defined as the horizontal distance between the elbow joint centre and the vector extending through the right and left shoulder joint centres. Segment and joint kinematics including lateral trunk lean, axial trunk rotation, sagittal position of the trunk (i.e., anterior or posterior tilt), horizontal abduction/adduction of the glenohumeral joint, and vertical abduction/adduction of the glenohumeral joint, and the elbow varus moment and glenohumeral internal rotation moment were also included as variables of interest for this study.

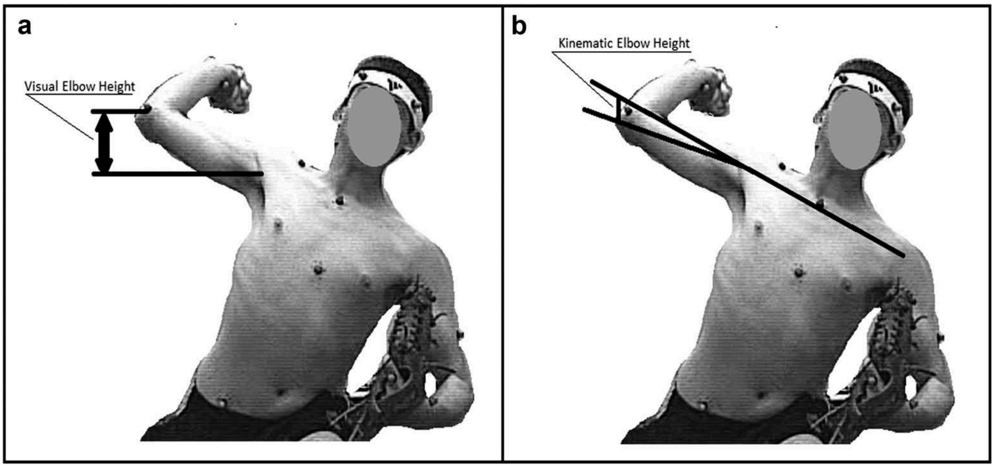

Figure 1. (a) Definition of vertical elbow position based on a visual assessment. (b) Definition of vertical elbow position based on the kinematic definition.

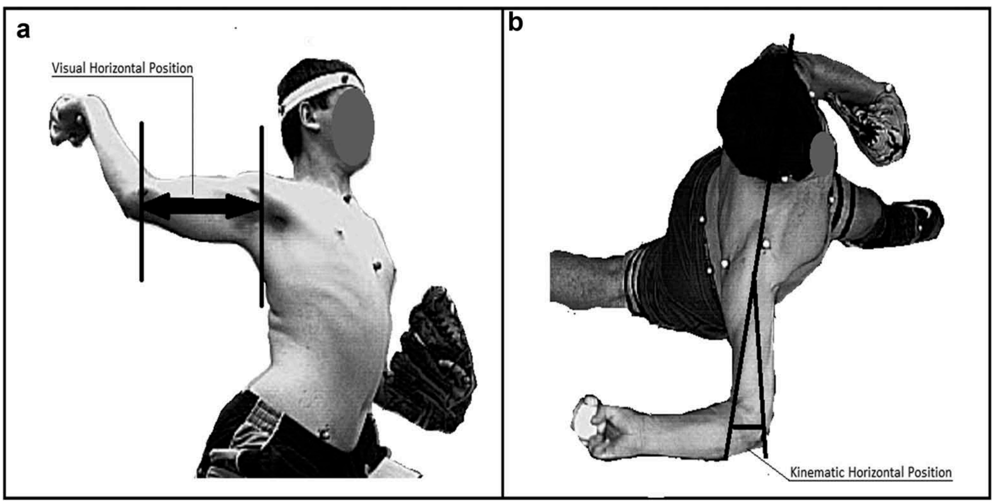

Figure 2. (a) Definition of horizontal elbow position based on a visual assessment. (b) Definition of horizontal elbow position based on the kinematic definition.

Descriptive statistics were computed for all variables of interest and the means and standard deviations are presented throughout this work. All variables of interest in this study were computed at the time of maximal external rotation (MER). MER was chosen as the time point of interest, as it is easily identified from video analysis. A Pearson's correlation was used to determine if visual elbow position was correlated with kinematic elbow position, and to determine if visual or kinematic elbow positions were correlated with glenohumeral and trunk kinematics. To determine if there were associations between the variables of interest and visual and kinematic elbow position a random intercept mixed effects regression model was used (Goldstein et al., 2002; Greenland, 2000). This model was used because it is capable of taking into account repeated measures using all available trials, thus increasing the precision of the model and appropriately accounting for variations in the standard error. A p-value of 0.05 or less was considered as a statistically significant association.

Results

This study included 99 college-aged male pitchers (with a mean age of 19.9 ± 1.4 years). The average fastball velocity was 32.1 ± 1.9 m/s. Descriptive statistics were computed for the variables of interest and are included in Table 2.

The results of the Pearson's correlations indicated that visual vertical elbow position was not correlated with kinematic vertical elbow position (r = 0.03, p = 0.768) nor was it correlated with the glenohumeral vertical abduction angle (r = 0.001, p = 0.992). However, visual vertical elbow position was well correlated with lateral trunk lean (r = 0.74, p < 0.001). A similar pattern was also noted with visual horizontal elbow position. Results indicated that the horizontal elbow position was not correlated with kinematic horizontal elbow position (r = 0.06, p = 0.555), nor was it correlated with the glenohumeral horizontal abduction angle (r = 0.02, p = 0.844). However, visual horizontal elbow position was correlated with axial trunk rotation (r = 0.51, p < 0.001). Sagittal trunk tilt was significantly correlated with both visual vertical elbow position (r = 0.33, p < 0.001) and visual horizontal elbow position (r = 0.22, p = 0.032).

The results of the Pearson's correlations indicated that kinematic vertical elbow position was highly correlated with the glenohumeral vertical abduction angle (r = 0.77, p < 0.001), but was independent of lateral trunk lean (r = 0.04, p = 0.694), and sagittal trunk tilt (r = 0.01, p = 0.913). Similarly, kinematic horizontal elbow position was highly correlated with the glenohumeral horizontal abduction angle (r = 0.98, p < 0.001), but was not correlated with axial trunk rotation (r = 0.01, p = 0.922), or sagittal trunk tilt (r = 0.12, p = 0.244).

The results of the regression analysis indicate that visual vertical elbow position was significantly associated with the maximum elbow varus moment (p = 0.001, β = 0.46). The association indicated that for every 1 cm increase in vertical elbow position (i.e., the pitcher's elbow joint is higher than their shoulder joint), the elbow varus moment increased by 0.46 Nm. Visual vertical elbow position was not associated with the glenohumeral internal rotation moment (p = 0.748) or ball velocity (p = 0.168). Visual

Table 2. Descriptive statistics (mean and standard deviation) for variables of interest.

Descriptive statistics for selected parameters	
Maximum Elbow Varus Moment (Nm)	76.2 ± 15.4
Glenohumeral Internal Rotation Moment (Nm)	77.5 ± 15.2
Visual Vertical Elbow Position (cm)	8.4 ± 6.9
Visual Horizontal Elbow Position (cm)	0.2 ± 3.6
Kinematic Vertical Elbow Position (cm)	5.6 ± 11.1
Kinematic Horizontal Elbow Position (cm)	9.8 ± 4.8
Lateral Trunk Lean (°)	18 ± 12
Axial Trunk Rotation (°)	3 ± 10
Sagittal Plane Anterior Trunk Tilt (°)	17 ± 10
Glenohumeral Vertical Adduction (°)	77 ± 24
Glenohumeral Horizontal Abduction (°)	19 ± 9

horizontal elbow position was not associated with the either the elbow varus moment ($p = 0.279$) or the glenohumeral internal rotation moment ($p = 0.509$). However, visual horizontal elbow position was significantly associated with ball velocity ($p = 0.019$, $\beta = 0.09$) and the association indicated that for every 1 cm increase in horizontal position (i.e., the pitchers elbow joint was more in line with the pitcher's shoulder joint), ball velocity decreased by 0.09 m/s.

It is also important to point out that visual vertical elbow position was positively associated with lateral trunk lean away from the pitching arm ($p < 0.001$, $\beta = 0.46$) indicating that for every 10° increase in lateral lean away from the pitching arm the elbow appeared to be 4.6 cm higher than the shoulder joint. Vertical elbow position was also positively associated with sagittal plane trunk tilt ($p < 0.001$, $\beta = 0.22$), indicating that for every 10° increase in anterior trunk tilt the elbow appeared to be 2.2 cm higher than the shoulder joint. Similarly, visual horizontal elbow position was associated with axial trunk rotation ($p < 0.001$, $\beta = 0.45$), indicating that for every 10° increase in axial trunk rotation (i.e., the pitcher was more open to home plate) that the elbow appeared to fall behind the shoulder by 4.5 cm. Horizontal elbow position was also associated with sagittal plane trunk tilt ($p < 0.001$, $\beta = 0.09$), indicating that for every 10° of increased anterior trunk tilt the elbow appeared to fall behind the shoulder by 0.9 cm.

The regression analysis indicated that kinematic vertical elbow position was not associated with the elbow varus moment ($p = 0.118$), the glenohumeral internal rotation moment ($p = 0.354$), or with ball velocity ($p = 0.890$). Kinematic vertical elbow position was also not associated with the lateral trunk lean ($p = 0.918$) nor with sagittal plane trunk tilt ($p = 0.055$). Similarly, kinematic horizontal elbow position was not associated with the elbow varus or glenohumeral internal rotation moment ($p = 0.993$, $p = 0.120$, respectively), nor was it associated with ball velocity ($p = 0.373$), axial trunk rotation ($p = 0.298$), or sagittal plane trunk tilt ($p = 0.861$).

Discussion and implications

The purpose of this study was to understand the implications of trunk position on elbow position. This study attempted to further explore the implications of visually assessing elbow position in isolation compared to kinematically assessing elbow position using three-dimensional biomechanical modelling, which took into account trunk position. An understanding of the methods used to assess elbow position and their association with performance (i.e., ball velocity) and injury potential (i.e., increased joint moments) are important to ensure that coaches and trainers make the appropriate corrections to a pitcher's mechanics to modify arm position. The results of this study show that the assessment of elbow position in isolation is very different than the kinematic definition of elbow position accounting for trunk orientation. These differences have significant implications for coaches and trainers.

The results of this study demonstrated that there was a significant difference between the visual assessment and kinematic assessment of elbow position which is corroborated by previous studies that indicated that further kinematic analysis is necessary to fill in current gaps in knowledge (Atwater, 1979). The results of this study indicated a lack of a direct association between visual vertical elbow position and kinematic vertical elbow position. This finding was likely caused by a strong correlation between lateral trunk lean and visual vertical elbow position indicating that visual assessment of a single segment alone might not be adequate enough to accurately assess a pitcher's mechanics. For example, a pitcher that laterally leans away from their throwing arm may appear to have a visually higher elbow relative to the shoulder despite no changes to shoulder abduction. In order to more accurately define elbow height, it is necessary to take into account trunk position. Kinematic elbow position does this by accounting for the changes in trunk position as evidenced by the fact that there were no correlations or associations between the trunk and vertical elbow position. Therefore, visual elbow position may be an important visual indicator of poor lateral trunk lean and an excessive anterior trunk tilt. Additionally, the result of the regression analysis indicated a significant increase in the elbow varus moment as vertical elbow position increases. This finding makes intuitive sense when the lateral trunk position is also taken into account as increased lateral trunk lean away from the pitching arm increases the appearance of a 'high elbow', as well as the fact that previous studies have indicated that increased lateral lean away from the pitching arm substantially increases the elbow varus moment (Oyama et al., 2013; Solomito et al., 2015). Therefore, what may appear as a 'high elbow' may not be caused by poor arm alignment but rather is caused by excessive lateral trunk lean. This finding suggests that coaches that visually, see a 'high elbow' should work with the pitcher on improving trunk position and core strength before modifying the pitcher's arm slot. These findings are consistent with previous studies that indicated that lateral trunk lean was greatest in pitchers with an overhead arm slot, and lowest in the pitchers throwing side arm (Escamilla et al., 2018). Additionally, it was also noted that overhand slot pitchers also had the greatest anterior trunk tilt (Escamilla et al., 2018).

Similarly, there was no direct relationship between visual horizontal elbow position and kinematic horizontal elbow position. The results of the regression analysis also indicated that axial trunk rotation was highly associated with the appearance that the elbow was either even with or slightly behind the plane of the body. Therefore, the visual horizontal positioning of the elbow may be an important visual indicator of poor axial rotation sequencing for a baseball pitcher which is also difficult to directly assess on field. Additionally, the results indicated that the more the elbow visually 'drags' behind the body the slower the ball velocity. Incorrect rotational sequencing has been previously shown to negatively affect ball velocity (Oyama et al., 2014; Stodden et al., 2001; Urbin et al., 2013), which supports the findings of this study. Therefore, coaches can use horizontal arm position not only as a means of correcting rotational sequencing issues but also as a means of improving a pitcher's ball velocity.

Interestingly the results of this work indicated that there were no associations between upper extremity joint moments or ball velocity when elbow position was kinematically defined. Since the difference between the kinematic and visual definitions of elbow position revolves around the inclusion of trunk position in the calculations, these findings further support the idea that the trunk plays a major role in pitching mechanics (Aguinaldo et al., 2007; Matsuo et al., 2006; Oyama et al., 2013; 2014; Solomito et al., 2018; 2015; Stodden et al., 2001). Additionally, the results of this study also seem to suggest that elbow position is not important in comparison to the position of the trunk. However, caution should be taken when interpreting the results in this way as the study cohort was comprised of Division I and III NCAA pitchers, who should be using proper mechanics and arm slots to have made it to this level of competition. Therefore, additional work on this topic should be performed in youth pitchers that are still developing appropriate pitching mechanics to fully understand the implications of elbow positioning.

This study does have limitations. The results of this study were based on the fastball motion only. Therefore, we do not know if these results can be applied to other pitch types. The pitcher's had an average age of 20 and therefore generalising our findings to adolescent or professional pitchers is not appropriate without further study. This study was performed in the motion analysis laboratory with limitations inherent in that research setting; however, these limitations were addressed by allowing pitchers adequate time to become acclimated to the testing conditions and by using a regulation mound as well as placing the target 60 feet 6 inches away. The pitching velocity reported in this work may appear to be lower than expected for this level of pitcher, however, the low-ball velocity is caused by the addition of motion analysis markers on the baseball which is known to slow the ball by up to 3 m/s (Solomito et al., 2019); however, all participants pitched using an instrumented ball allowing for the study results to be comparable across all participants. Finally, there have been a number of studies that have indicated that the visual assessment alone may not be adequate to fully identify mechanical flaws within the pitching cycle (Christoffer et al., 2019; Nicholls et al., 2003; Oyama, 2012), and therefore accurately assessing visual positioning as described in this paper may also be difficult. However, a paper by Nicholls et al. did indicate that visual assessment through 2D high-speed video analysis could be used to adequately assess trunk lean (Nicholls et al., 2003).

Conclusion

The results of this study indicated that there is a difference in the visual and kinematic interpretations of elbow position. The results of this study further highlight the important role that the trunk plays in pitching mechanics. More importantly, however, is that this study indicates that the visual interpretation of the elbows position, specifically a high elbow, or a dragging elbow, could be used to key a baseball coach or trainer to a potentially more serious issue with a pitcher's rotational sequencing or lateral trunk positioning. For example, instead of correcting a pitcher's high elbow, a coach may focus on improving lateral trunk positioning either through coaching or improving core strength to help a pitcher maintain a more upright position. Therefore, in the absence of motion analysis tools, visual indicators, such as elbow position, could be used to more appropriately correct poor mechanics.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Aguinaldo, A. L., Buttermore, J., & Chambers, H. (2007). Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *Journal of Applied Biomechanics*, *23*, 42–51. doi:10.1123/jab.23.1.42

Aguinaldo, A. L., & Chambers, H. (2009). Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *The American Journal of Sports Medicine*, *37*, 2043–2048. doi:10.1177/0363546509336721

Albright, J. A., Jokl, P., Shaw, R., & Albright, J. P. (1978). Clinical study of baseball pitchers: Correlation of injury to the throwing arm with method of delivery. *The American Journal of Sports Medicine*, *6*, 15–21. doi:10.1177/036354657800600104

Atwater, A. E. (1979). Biomechanics of overarm throwing movements and of throwing injuries. *Exercise and Sport Sciences Reviews*, *7*, 43–86. doi:10.1249/00003677-197900070-00004

Chalmers, P. N., Wimmer, M. A., Verma, N. N., Cole, B. J., Romeo, A. A., Cvetanovich, G. L., & Pearl, M. L. (2017). The relationship between pitching mechanics and injury: A review of current concepts. *Sports Health*, *9*, 216–221. doi:10.1177/1941738116686545

Christoffer, D. J., Melugin, H. P., & Cherny, C. E. (2019). A clinician's guide to analysis of the pitching motion. *Current Reviews in Musculoskeletal Medicine*, *12*, 98–104. doi:10.1007/s12178-019-09556-4

Conte, S., Camp, C. L., & Dines, J. S. (2016). Injury trends in major league baseball over 18 seasons: 1998-2015. *American Journal of Orthopedics*, *45*, 116–123.

Escamilla, R. F., Slowik, J. S., Diffendaffer, A. Z., & Fleisig, G. S. (2018). Differences among overhand, three-quarter, and sidearm pitching biomechanics in professional baseball players. *Journal of Applied Biomechanics*, *34*, 1–27. doi:10.1123/jab2017-0211

Fleisig, G. S. (1994). *The biomechanics of baseball pitching*. University of Alabama Press.

Fleisig, G. S., Andrews, J. R., Cutter, G. R., Weber, A., Loftice, J., McMichael, C., Hassell, N., & Lyman, S. (2011). Risk of serious injury for young baseball pitchers: A 10-year prospective study. *The American Journal of Sports Medicine*, *39*, 253–257. doi:10.1177/0363546510384224

Fleisig, G. S., Andrews, J. R., Dillman, C. J., & Escamilla, R. F. (1995). Kinetics of baseball pitching with implications about injury mechanisms. *The American Journal of Sports Medicine*, *23*, 233–239. doi:10.1177/036354659502300218

Fleisig, G. S., Kingsley, D. S., Loftice, J. W., Dinnen, K. P., Ranganathan, R., Dun, S., Escamilla, R. F., & Andrews, J. R. (2006). Kinetic comparison among the fastball, curveball, change-up, and slider in collegiate baseball pitchers. *The American Journal of Sports Medicine*, *34*, 423–430. doi:10.1177/0363546505280431

Goldstein, H., Browne, W., & Rasbash, J. (2002). Multilevel modelling of medical data. *Statistics in Medicine*, *21*, 3291–3315. doi:10.1002/sim.1264

Greenland, S. (2000). Principles of multilevel modelling. *International Journal of Epidemiology*, *29*, 158–167. doi:10.1093/ije/29.1.158

Greenwood, D. T. (1988). *Principles of dynamics*. Prentice-Hall.

Gugenheim, J., Jr, Stanley, R. F., Woods, G. W., & Tullos, H. S. (1976). Little league survey: The houston study. *The American Journal of Sports Medicine*, *4*, 189–200. doi:10.1177/036354657600400501

House, T. (2000). *The pitching edge*. Human Kinetics.

House, T., Heil, G., & Johnson, S. (2006). *The art and science of pitching* (Coaches choice series, coaches choice). Champaign, IL: Human Kinetics.

House, T., & Thorburn, D. (2008). *Arm action, arm path, and the perfect pitch: Building a million-dollar arm* (Coaches choice). Monterey, CA: Coaches Choice.

Kamineni, S., ElAttrache, N. S., O'Driscoll, S. W., Ahmad, C. S., Hirohara, H., Neale, P. G., an, K.-N., & Morrey, B. F. (2004). Medial collateral ligament strain with partial posteromedial olecranon resection: A biomechanical study. *Journal of Bone and Joint Surgery*, *86*, 2424–2430. doi:10.2106/00004623-200411000-00010

Levin, J. S., Zheng, N., Dugas, J. R., Cain, E. L., Jr., & Andrews, J. C. (2004). Posterior olecranon resection and ulnar collateral ligament strain. *Journal of Shoulder and Elbow Surgery*, *13*, 66–71. doi:10.1016/j.jse.2003.09.010

Lyman, S., Fleisig, G. S., Waterbor, J. W., Funkhouser, E. M., Pulley, L., Andrews, J. R., Osinski, E. D., & Roseman, J. M. (2001). Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Medicine and Science in Sports and Exercise*, *33*, 1803–1810. doi:10.1097/00005768-200111000-00002

Mahure, S. A., Mollon, B., Shamah, S. D., Kwon, Y. W., & Rokito, A. S. (2016). Disproportionate trends in ulnar collateral ligament reconstruction: Projections through 2025 and a literature review. *Journal of Shoulder and Elbow Surgery*, *25*, 1005–1012. doi:10.1016/j.jse.2016.02.036

Matsuo, T., Fleisig, G. S., Zheng, N., & Andrews, J. R. (2006). Influence of shoulder abduction and lateral trunk tilt on peak elbow varus torque for college baseball pitchers during simulated pitching. *Journal of Applied Biomechanics*, *22*, 93–102.

Matsuo, T., Matsumoto, T., Mochizuki, Y., Takada, Y., & Saito, K. (2002). Optimal shoulder abduction angles during baseball pitching from maximal wrist velocity and minimal kinetic viewpoints. *Journal of Applied Biomechanics*, *18*, 306–320. doi:10.1123/jab.18.4.306

Nicholls, R., Fleisig, G., Elliott, B., Lyman, S., & Osinski, E. (2003). Baseball: Accuracy of qualitative analysis for assessment of skilled baseball pitching technique. *Sports Biomechanics*, *2*, 213–226. doi:10.1080/14763140308522819

Nissen, C. W., Westwell, M., Õunpuu, S., Patel, M., Solomito, M., & Tate, J. (2009). A biomechanical comparison of the fastball and curveball in adolescent baseball pitchers. *The American Journal of Sports Medicine*, *37*, 1492–1498. doi:10.1177/0363546509333264

Nissen, C. W., Westwell, M., Ounpuu, S., Patel, M., Tate, J. P., Pierz, K., Bicos, J., & BICOS, J. (2007). Adolescent baseball pitching technique: A detailed three-dimensional biomechanical analysis. *Medicine and Science in Sports and Exercise*, *39*, 1347–1357. doi:10.1249/mss.0b013e318064c88e

Oyama, S. (2012). Baseball pitching kinematics, joint loads, and injury prevention. *Journal of Sport and Health Science*, *1*, 80–91. doi:10.1016/j.jshs.2012.06.004

Oyama, S., Yu, B., Blackburn, J. T., Padua, D. A., Li, L., & Myers, J. B. (2013). Effect of excessive contralateral trunk tilt on pitching biomechanics and performance in high school baseball pitchers. *The American Journal of Sports Medicine*, *41*, 2430–2438. doi:10.1177/0363546513496547

Oyama, S., Yu, B., Blackburn, J. T., Padua, D. A., Li, L., & Myers, J. B. (2014). Improper trunk rotation sequence is associated with increased maximal shoulder external rotation angle and shoulder joint force in high school baseball pitchers. *The American Journal of Sports Medicine*, *42*, 2089–2094. doi:10.1177/0363546514536871

Saper, M. G., Pierpoint, L. A., Liu, W., Comstock, R. D., Polousky, J. D., & Andrews, J. R. (2018). Epidemiology of shoulder and elbow injuries among United States high school baseball players: School years 2005-2006 through 2014-2015. *The American Journal of Sports Medicine*, *46*, 37–43. doi:10.1177/0363546517734172

Solomito, M., Garibay, E., Golan, E., & Nissen, C. (2019). Elbow flexion post ball release is associated with the elbow varus deceleration moments in baseball pitching. *Sports Biomechanics*. doi:10.1080/14763141.2018.1560495

Solomito, M. J., Garibay, E. J., & Nissen, C. W. (2018). Sagittal plane trunk tilt is associated with upper extremity joint moments and ball velocity in collegiate baseball pitchers. *Orthopaedic Journal of Sports Medicine*, *6*, 2325967118800240. doi:10.1177/2325967118800240

Solomito, M. J., Garibay, E. J., Õunpuu, S., Tate, J. P., & Nissen, C. W. (2013). A biomechanical evaluation of the kinetics for multiple pitching techniques in college-aged pitchers. *Orthopaedic Journal of Sports Medicine*, *1*, 2325967113508255. doi:10.1177/2325967113508255

Solomito, M. J., Garibay, E. J., Woods, J. R., Õunpuu, S., & Nissen, C. W. (2015). Lateral trunk lean in pitchers affects both ball velocity and upper extremity joint moments. *The American Journal of Sports Medicine*, *43*, 1235–1240. doi:10.1177/0363546515574060

Stodden, D. F., Fleisig, G. S., McLean, S. P., Lyman, S. L., & Andrews, J. R. (2001). Relationship of pelvis and upper torso kinematics to pitched baseball velocity. *Journal of Applied Biomechanics*, *17*, 164–172. doi:10.1123/jab.17.2.164

Urbin, M., Fleisig, G. S., Abebe, A., & Andrews, J. R. (2013). Associations between timing in the baseball pitch and shoulder kinetics, elbow kinetics, and ball speed. *The American Journal of Sports Medicine*, *41*, 336–342. doi:10.1177/0363546512467952

Werner, S. L., Murray, T. A., Hawkins, R. J., & Gill, T. J. (2002). Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. *Journal of Shoulder and Elbow Surgery*, *11*, 151–155. doi:10.1067/mse.2002.121481