Stride-Phase Kinematic Parameters That Predict Peak Elbow Varus Torque

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Background: During baseball pitching, a high amount of elbow varus torque in the arm cocking-to-acceleration phase is thought to be a biomechanical risk factor for medial elbow pain and injury. The biomechanics of the stride phase may provide preparation for the arm cocking-to-acceleration phase that follows it.

Purpose: To determine the kinematic parameters that predict peak elbow varus torque during the stride phase of pitching.

Study Design: Descriptive laboratory study.

Methods: Participants were 107 high school baseball pitchers (age range, 15-18 years) without shoulder or elbow problems. Whole-body kinematics and kinetics during fastball pitching were analyzed using 3-dimensional measurements from 36 retroreflective markers. A total of 26 kinematic parameters of the upper and lower limbs during the stride phase leading up to the stride foot contact were extracted for multiple regression analysis to assess their combined effect on the magnitude of peak elbow varus torque.

Results: Increased wrist extension, elbow pronation, knee flexion on the leading leg, knee extension on the trailing leg at stride foot contact, and upward displacement of the body’s center of mass in the stride phase were significantly correlated with decreased peak elbow varus torque (all \(P < .05\)). Moreover, 38% of the variance in peak elbow varus torque was explained by a combination of these 5 significant kinematic variables (\(P < .001\)).

Conclusion: We found that 5 kinematic parameters during the stride phase and the combination of these parameters were associated with peak elbow varus torque. The stride phase provides biomechanical preparation for pitching and plays a key role in peak elbow varus torque in subsequent pitching phases.

Clinical Relevance: The present data can be used to screen pitching mechanics with motion capture assessment to reduce peak elbow varus torque. Decreased peak elbow varus torque is expected to reduce the risk of elbow medial pain and injury.

Keywords: baseball; elbow; fastball; injury; pain; pitcher; torque; varus; valgus

High school baseball players are prone to elbow pain and injury due to cumulative mechanical stress on the elbow joint with repetitive throwing.43 Additionally, elbow pain during baseball pitching significantly increases the risk of developing elbow injury, although a number of pitchers continue pitching despite arm or elbow pain.26,32,51 Therefore, ulnar collateral ligament tears, medial epicondylitis, ulnar neuritis, osteochondral dissecans, and posterolateral instability are not uncommon in high school baseball pitchers.6,12,15,21,32,36

A high magnitude of varus torque on the elbow joint during baseball pitching can predispose players to elbow pain and injury.16 High school baseball pitchers generate approximately 48 to 60 N m of peak elbow varus torque around the point of maximum external rotation of the throwing shoulder in the arm acceleration phase.17,31,34 Additionally, specific pitching techniques lead to increased force and torque acting on the elbow.3,9,10,14,29,34,46 Meister29 reported that improper pitching mechanics beginning with the time of stride foot contact (SFC) can lead to increased elbow varus torque. Specifically, greater external rotation or abduction of the pitching shoulder at SFC,14,46 early onset of trunk rotation in relation to SFC,3,10 lower forward flexion of the trunk at SFC,34 and the forearm in supination and the open-shoulder position during the stride phase9 are related to increased peak elbow varus torque. The results of previous studies have established that elbow varus torque during fastball pitching is a modifiable risk factor. However, the biomechanical factors required to reduce peak elbow varus torque, considering motion patterns of the lower limb, have not been elucidated.

Kinematic factors during the stride phase of pitching are easily observed and are commonly discussed among pitching coaches because the stride phase leading up to SFC
likely provides the biomechanical preparation for the arm cocking to arm acceleration phases, where the greatest forces and torques are experienced by the throwing elbow. Therefore, to decrease players’ risk of pitching-related elbow pain and injury, coaches should encourage proper pitching mechanics, including a decrease in peak elbow varus torque during the stride phase, and should limit pitch counts to avoid excessive strain and fatigue for muscles, tendons, and ligaments.25,43,51

This study aimed to determine the upper and lower limb kinematic parameters in the stride phase that would alter peak elbow varus torque in high school baseball pitchers. We hypothesized that the best-fit combination of upper and lower limb kinematic parameters in the stride phase would reduce the magnitude of peak elbow varus torque.

METHODS

Participants

The research protocol for this study received institutional review board approval. Before testing, a total of 107 high school baseball pitchers from local baseball leagues provided written informed consent/assent, and parental consent was obtained.

The mean pitcher age, height, and body weight were 16.3 ± 0.8 years (range, 15-18 years), 174.9 ± 5.5 cm, and 66.9 ± 6.6 kg, respectively. Pitchers were excluded from participating in this study if they had a history of (1) shoulder or elbow surgery, (2) shoulder or elbow pain lasting >2 weeks, (3) shoulder or elbow pain that prevented them from participating in a game or practice, or (4) recurrent shoulder or elbow pain. All pitchers were accustomed to pitching fastballs using the pitching rubber on the regulation pitching mound. Their pitching styles were only overarm and three-quarter deliveries.

Data Collection of Baseball Pitching

A 3-dimensional (3D) quantitative baseball pitching evaluation was performed at our institution. The pitchers underwent a preparation routine of running, stretching, and warm-up pitching; all pitchers wore tight-fitting shorts, baseball socks, and a baseball cap but no shirt. To measure kinematics and kinetics of the upper and lower limbs during fastball pitching, we securely placed 36 bilateral retroreflective markers (14 mm in diameter) on the skin overlying anatomic landmarks at the head, trunk, upper arm, forearm, hand, pelvis, thigh, shank, and foot segments. We attached 3 markers to the baseball cap on the top, right, and left sides of the head, whereas 2 markers were attached to each heel and over the third metatarsal styloid process of the foot. These marker placements were determined as previously defined.30,44,45

A motion-capture 3D automatic digitizing system with 7 charge-coupled-device synchronized cameras (ProReflex MCU-500; Qualisys Inc) was installed around a real pitching mound (Figure 1) and used to record 3D positions from the retroreflective markers during baseball pitching in an indoor laboratory (width × height × length: 11.6 × 3.9 × 26.5 m).

Figure 1. A schematic of the measurement system for baseball pitching and the laboratory fixed axis. CAM, charge-coupled-device high-speed camera; HVC, high-speed video camera. +XG is directed toward home base; +YG is directed toward first base.

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Ethical approval for this study was obtained from Nobuhara Hospital and Institute of Biomechanics (study No. E172).
During the pitch, all 3D positional data of the retroreflective markers were tracked at a rate of 500 frames per second while the ball speed was measured using an ultrasonic radar gun (Speed Max 2; Mizuno Corp). Simultaneously, 2 synchronized high-speed video cameras (HSV-500C3; NAC Image Technology Inc) using 250 frames per second captured the diagonal forward and backward views of the pitching motion. Therefore, SFC could be defined as the point when the bottom of the leading foot clearly contacted the pitching mound in 2 different views, according to a previously described procedure. Subsequently, the position of whole-body CoM was calculated by the weighted average of all segment CoM positions using a subset of 3D positional data from the measured markers. For this calculation, we considered anthropometric reference data including body segment definition, segment mass fraction of the body, and the center position of segment mass as a segment length fraction from the endpoint of the distal segment or proximal segment. Subsequently, ∆CoM during baseball pitching was calculated as the global position of CoM at the time of SFC subtracted from the global position of CoM at the time of the highest position of the knee on the leading leg; this calculation entailed ∆CoM in the pitching or second-base direction (∆CoMx), ∆CoM in the first- or third-base direction (∆CoMy), and ∆CoM in the upward or downward direction (∆CoMz). These were expressed as ∆BH.

Kinematic and Kinematic Analysis

The upper and lower body kinematics and kinetics during fastball pitching were calculated using the measured 3D positional data from the retroreflective markers. The local coordinate systems of the hand, forearm, upper arm, trunk, pelvis, thigh, shank, and foot segments were set to analyze the 3D joint rotations (angular displacement) for each pitching trial. These systems were determined mathematically by a subset of 3D locations of the measured markers. Subsequently, the clinical conventions of the trunk, shoulder, elbow, wrist, pelvis, hip, and knee joint angles were identified using joint coordinate system calculations (Figure 2). Pelvic rotation was determined only relative to the laboratory fixed-coordinate system. All other 3D joint rotational measurements of the distal segments were calculated relative to the proximal coordinate system. In particular, the joint rotations of the shoulder could be described as humerothoracic rotations. For joint angle convention of knee flexion-extension, full flexion of the knee represented 0°, and full extension was 180°. For joint angle convention of the elbow flexion-extension, full flexion of the elbow was 180°, and full extension was 0°.

To analyze pitching kinematics in the stride phase, the pitching phase was divided into 6 subphases: wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. Subsequently, stride length, foot angle, foot position, onset time of trunk rotation, and the position of the whole-body center of mass (CoM) were calculated to investigate the influence of these parameters on peak elbow varus torque. The stride length was the distance between the center position of the bilateral ankle markers on the trailing leg at the time of the highest position of the knee on the leading leg and that on the leading leg at the time of SFC. Subsequently, this was expressed as a percentage of the participant’s body height (%BH). The foot angle and foot position could be indicated by the direction in which the leading foot contacted the pitching mound. The onset time of trunk rotation was defined as the point during which the magnitude of trunk rotation began to decrease from its maximum value in reference to the time of SFC. To obtain the position of the whole-body CoM in relation to the laboratory fixed-axis during pitch, the human body was assumed as a system of rigid bodies, with 15 segments representing the whole body (head; upper and lower torso; bilateral upper arm, forearm, hand; and bilateral upper leg, lower leg, and foot). Subsequently, the position of whole-body CoM was calculated using joint coordinate system calculations (Figure 2). Pelvic rotation was determined only relative to the laboratory fixed-coordinate system. All other 3D joint rotational measurements of the distal segments were calculated relative to the proximal coordinate system. In particular, the joint rotations of the shoulder could be described as humerothoracic rotations. For joint angle convention of knee flexion-extension, full flexion of the knee represented 0°, and full extension was 180°. For joint angle convention of the elbow flexion-extension, full flexion of the elbow was 180°, and full extension was 0°.

Statistical Analysis

A standard statistical analysis software package (SPSS Base Version 15; IBM Corp) was used to investigate the combined effect of shoulder, elbow, wrist, trunk, pelvis, hip, and knee motions on the magnitude of peak elbow varus torque via stepwise multiple linear regression. Accordingly, 26 kinematic data points in association with SFC and the stride phase for independent variables were extracted from the processed data: shoulder external-internal rotation, abduction, and horizontal adduction-abduction; elbow supination-pronation and flexion; wrist radial-ulnar deviation and flexion-extension; trunk backward-forward flexion, lateral-contralateral tilt, and lateral rotation; pelvis lateral rotation; hip flexion-extension, external-internal rotation, and abduction-adduction on the leading and trailing legs; knee flexion on the leading and trailing legs; stride length; foot angle; foot position; ∆CoMx; ∆CoMy; ∆CoMz;
RESULTS

The mean peak elbow varus torque across 107 pitchers was $5.0 \pm 1.2 \% \text{BWH}$ ($57.0 \pm 15.7 \text{ N-m}$) around the point of maximum external rotation of the throwing shoulder. A weak positive association was found between peak elbow varus torque and ball speed ($R^2 = 0.05; P < .001$) on simple linear regression. The mean ball speed across all trials for the 107 pitchers was $120.2 \pm 5.5 \text{ km/h}$ ($74.7 \pm 5.5 \text{ mph}$).

From the final predictive model by the linear stepwise multiple regression analysis, the adjusted $R^2$ value was $0.38 (P < .001)$, indicating that 38% of the variance in peak elbow varus torque was explained. Five kinematic variables—increased wrist extension at SFC, upward displacement in $\Delta \text{CoM}_z$ during the stride phase, knee flexion on the leading leg at SFC, knee extension on the trailing leg at SFC, and elbow pronation at SFC—were identified as the most significant biomechanical factors contributing to decreased magnitude of peak elbow varus torque (Table 1). Additionally, 3 significant kinematic variables were unrelated to ball speed and 2 significant variables—increased

$\Delta \text{CoM}_z$; and onset time of trunk rotation. $P < .05$ was considered statistically significant.
At stride phase of whole-body center of mass in the upward or downward direction. The regression equation for predicting peak elbow varus torque was as follows:

\[
\text{PEVT} = 5.379 + (0.027 \times \text{WFE at SFC}) – (0.062 \times \text{ACOM}_x \text{ upward at SFC}) – (0.035 \times \Delta \text{CoM}_x \text{ at SFC}) + (0.033 \times \text{KFL at SFC}) – (0.035 \times \text{KFT at SFC}) + (0.008 \times \text{ESP at SFC}),
\]

where PEVT is the peak elbow valgus torque, SFC is the stride foot contact, SP is the stride phase, WFE is the wrist flexion-extension at SFC, \(\Delta\text{CoM}_x\) is the displacement of whole-body center of mass in the upward or downward direction. The constant is statistically significant (\(p < .001\)).

DISCUSSION

Three previous studies created biomechanical predictors for decreasing peak elbow varus (resistance to valgus) torque during fastball pitching using multiple regression analysis. Werner et al.\(^4\) reported that peak elbow varus torque in professional baseball pitchers was most affected by shoulder abduction at SFC, peak shoulder horizontal adduction angular velocity, elbow flexion at the instant of peak elbow varus torque, and peak shoulder external rotation torque. Aguiñaldo and Chambers\(^3\) indicated that peak shoulder external rotation, elbow flexion at the time of peak elbow varus torque, and elbow varus loading rate increased peak elbow varus torque in skilled adult pitchers. Sabick et al.\(^4\) reported that the most significant factors in reducing varus torque exerted on the elbow in youth baseball pitchers included body weight, maximal shoulder internal rotation torque, maximal shoulder abduction torque, and maximal external shoulder rotation. Although it is a well-known theory that lower limb motion contributes to
baseball pitching mechanics, the influence of lower limb motion patterns on peak elbow varus torque has not been considered.

Given that the throwing arm motion is fastest during the arm acceleration phase, baseball pitchers may have difficulty changing their pitching kinematics and kinetics during this phase, as suggested by the previous study results. In addition, the biomechanical predictors for reducing peak elbow varus torque among high school baseball pitchers have not been investigated. From the viewpoint of pitching coaches, upper and lower limb kinematic parameters (eg, joint position and angle) are more easily observed than are kinetic parameters (eg, joint force and torque). Hence, our study focused simply on the kinematic patterns of the upper and lower limbs during the stride phase as biomechanical preparation in predicting peak elbow varus torque during the arm acceleration phase for high school baseball pitchers.

The current study found that the combination of increased wrist extension, knee flexion on the leading leg, knee extension on the trailing leg, elbow pronation at SFC, and upward displacement in CoMz during the stride phase had considerable ability to reduce the magnitude of peak elbow varus torque. Moreover, these 5 significant kinematic factors were responsible for 38% of the variance in peak elbow varus torque and likely had a weak effect on ball speed. Davis et al reported that a forearm in pronation leads to a decrease in peak elbow varus torque and had higher pitching efficiency. The flexor-pronator muscle group of the forearm functioned as the stabilizer for the elbow joint and contributed to resisting elbow valgus stress. Moreover, regarding dynamic stability of the ulnohumeral joint, Otoshi et al reported that isometric contraction of forearm pronator muscles in a simulated pitching position significantly decreased the ulnohumeral joint space, as shown on an ultrasonographic image. These previous studies support our finding that keeping the forearm in pronation at SFC leads to a decrease in peak elbow varus torque among pitchers.

Wrist palmar flexion contributes to dynamically resistant valgus torque. However, the results of previous studies on pitching biomechanics indicated that high school baseball pitchers used approximately 31° of wrist extension at SFC. The magnitude of elbow varus torque (resisting valgus) at SFC was significantly lower than that in the arm acceleration phase. Therefore, based on previous findings and our results, it is reasonable to infer that the wrist extension position at SFC has a biomechanical benefit in the arm acceleration phase for high school baseball pitchers.

The limited hip flexion and internal rotation motions in the leading and trailing legs are significantly related to elbow pain and adversely affect pitching biomechanics. However, our predictor excluded hip flexion and internal rotation motion on leading and trailing legs as significant parameters for reducing peak elbow varus torque. Instead, we found that knee flexion on the leading and knee extension on the trailing legs at SFC affected the magnitude of peak elbow varus torque, and the averaged knee flexion-extension on both legs at SFC was similar to that reported in previous studies. Matsuo et al assessed kinematic and temporal parameters during fastball pitching in collegiate and professional baseball pitchers and stated that pitchers in the high-velocity group performed greater knee extension angular velocity on the leading leg at the instant of ball release. Ramsey et al indicated that longer stride pitching (compared with shorter stride pitching) generated greater total body momentum and lower throwing arm momentum proportions during the arm acceleration phase owing to proximal-distal intersegmental momentum transfer mechanics, and those authors inferred that a longer stride was beneficial for mitigating throwing arm stress. Therefore, increased knee flexion on the leading leg at SFC leading to a decrease in peak elbow varus torque, as shown in the current study, probably provides the biomechanical preparation for knee extension at the time of ball release. Additionally, increased knee extension on the trailing leg at SFC may be related to increased stride length. Consequently, the kinematic parameters at SFC of both knees shown in the current study can improve performance and reduce elbow varus joint loading.

CoM kinematic parameters are significantly related to stability and balance control for human motion. However, limited data are available regarding the influence of CoM kinematics on increased versus decreased magnitude of peak elbow varus torque during fastball pitching. Although the downward displacement of COMz was found to be associated with increased peak elbow varus torque, it is unclear by what mechanism vertical displacement of the COMz during the stride phase affects varus loading at the elbow. Future research is required to investigate the causal relationship between the increased downward displacement in COMz during the stride phase and the increase in peak elbow varus torque. For this, the brachistochrone curve can be of assistance in comprehending the patterns and paths of COMz displacement during the stride phase.

In the next phase of our research, we will apply our findings to (1) identify any of the 5 kinematic parameters that are easily modified, (2) clarify how effective these modifications would be for decreasing the magnitude of peak elbow varus torque, and (3) investigate whether these modifications would result in faster or slower speed pitches. As well, a future study is warranted to identify the stride-phase pitching mechanism that results in the combination of the 5 significant kinematic parameters; such an investigation would involve the dynamic ranges of motion of upper and lower limbs during the stride phase and/or their respective maximal or minimal joint angles.

A few potential limitations of this study should be noted. First, because it was a retrospective study, we were limited to using only the available data. Second, we assumed that pitchers had the same pitching mechanics over time despite being starting pitchers or relief pitchers. Third, we collected data under simulated game settings. Accordingly, pitching kinematics and kinetics in the current study were likely to differ somewhat compared with those in a real game setting. In fact, ball velocities in this study were reduced compared with those that pitchers self-reported.
Fourth, our results may not be generalizable to younger or older pitchers. Fifth, a biomechanical predictor consisting of stride-phase kinematic parameters in the present study considered only fastball pitchers without fatigue. Sixth, elbow varus torque in the rigid body model was calculated as the summation of all torques generated around the elbow joint by skeletal muscles, tendons, ligaments, and other soft tissues. A future calculation model is needed to determine specific torques acting on each portion around the elbow joint.5

CONCLUSION

The current study was an evaluation of the biomechanical predictors and relationships relative to peak elbow varus torque during fastball pitching. The results showed that a combination of increased wrist extension, elbow pronation, knee flexion on the leading leg and knee extension on the trailing leg at the SFC, and upward displacement of the body’s center of mass in the stride phase directly decreased the peak elbow varus torque. Additionally, the 5 significant kinematic parameters were more likely to balance competing goals for reducing peak elbow varus torque and maintaining ball speed. A simple predictor as identified in the present study can be practical for screening upper and lower limb motions during fastball pitching to decrease the risk of pitching-related medial elbow problems in high school baseball pitchers.

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