Stride-Phase Kinematic Parameters That Predict Peak Elbow Varus Torque

Hiroshi Tanaka,*† PhD, Toyohiko Hayashi,‡ PhD, Hiroaki Inui,† MD, PhD,
Tomoyuki Muto,† MD, PhD, Kohnan Tsuchiyama,§ MD, Hiroki Ninomiya,† MD,
Yasuo Nakamura,‖ PhD, Syoji Kobashi,¶ PhD, and Katsuya Nobuhara,† MD, PhD

Investigation performed at Nobuhara Hospital and Institute of Biomechanics, Tatsuno, Japan

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] Meister[29] 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 time 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 phase[9] 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

The Orthopaedic Journal of Sports Medicine, 8(12), 2325967120968068
DOI: 10.1177/2325967120968068

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]

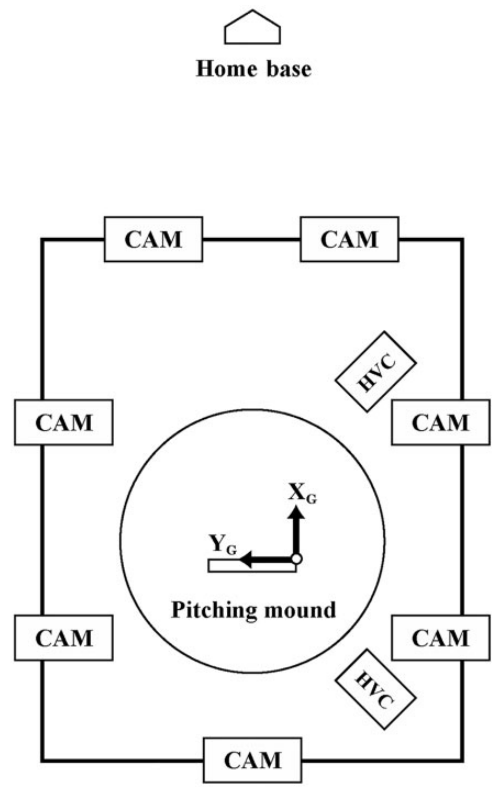

Figure 1. A schematic of the measurement system for baseball pitching and the laboratory fixed axis. CAM, charge-coupled-device high-speed camera; HVC, high-speed video camera. $+X_G$ is directed toward home base; $+Y_G$ is directed toward first base.

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).

*Address correspondence to Hiroshi Tanaka, PhD, Nobuhara Hospital and Institute of Biomechanics, 720 Haze, Issai-cho, Tatsuno-shi, Hyogo, 6794017, Japan (email: hirockman@hotmail.co.jp).
†Nobuhara Hospital and Institute of Biomechanics, Tatsuno, Japan.
‡Graduate School of Science and Technology, Niigata University, Niigata, Japan.
§Department of Orthopaedic Surgery, Hyogo College of Medicine, Nishinomiya, Japan.
||Faculty of Health and Sports Science, Doshisha University, Kyotanabe, Japan.
¶University of Hyogo, Himeji, Japan.
Final revision submitted June 11, 2020; accepted June 30, 2020.
The authors declared that there are no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.
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.[30,37]

For the pitching trials, each player continued to pitch 5 fastball pitches from the stretch under maximum effort to a catcher behind home plate placed at the regulation distance of 18.44 m from the pitching rubber. Participants were instructed to pitch as accurately as possible while aiming at the center of the strike zone. For each pitcher, the fastest pitch thrown that was closest to a strike was considered the best pitching performance and was kinematically and kinetically analyzed to represent the pitcher's fastball mechanics, as previously described.[7,30,44,45]

Kinetic 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.[49,50] 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.[11,19] 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.[13] 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.[13] 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.[2,3] 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 by the weighted average of all segment CoM positions using a subset of 3D positional data from the measured markers.[27,47] For this calculation, we considered anthropometric reference data[1] 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, ΔCoM 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 ΔCoM in the pitching or second-base direction (ΔCoM_x), ΔCoM in the first- or third-base direction (ΔCoM_y), and ΔCoM in the upward or downward direction (ΔCoM_z). These were expressed as %BH.

During the pitch, the varus torque acting on the pitching elbow (resisting valgus torque) was computed using an inverse dynamic technique,[16,30,44,45] where the input included kinematic data of the hand and forearm, individual body segment parameters,[1] and the calculated joint reaction force acting on the wrist and elbow. The weight of the baseball was considered as the point mass at the hand segment before it was released and was excluded from this segment after release. Subsequently, to compare data among the pitchers, elbow varus torque was expressed in an absolute unit (N·m) and normalized by body weight and height (%BWH). All kinematic and kinetic calculations were performed using customized scripts in MATLAB (R2018a; The MathWorks Inc).

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; ΔCoM_x; ΔCoM_y;

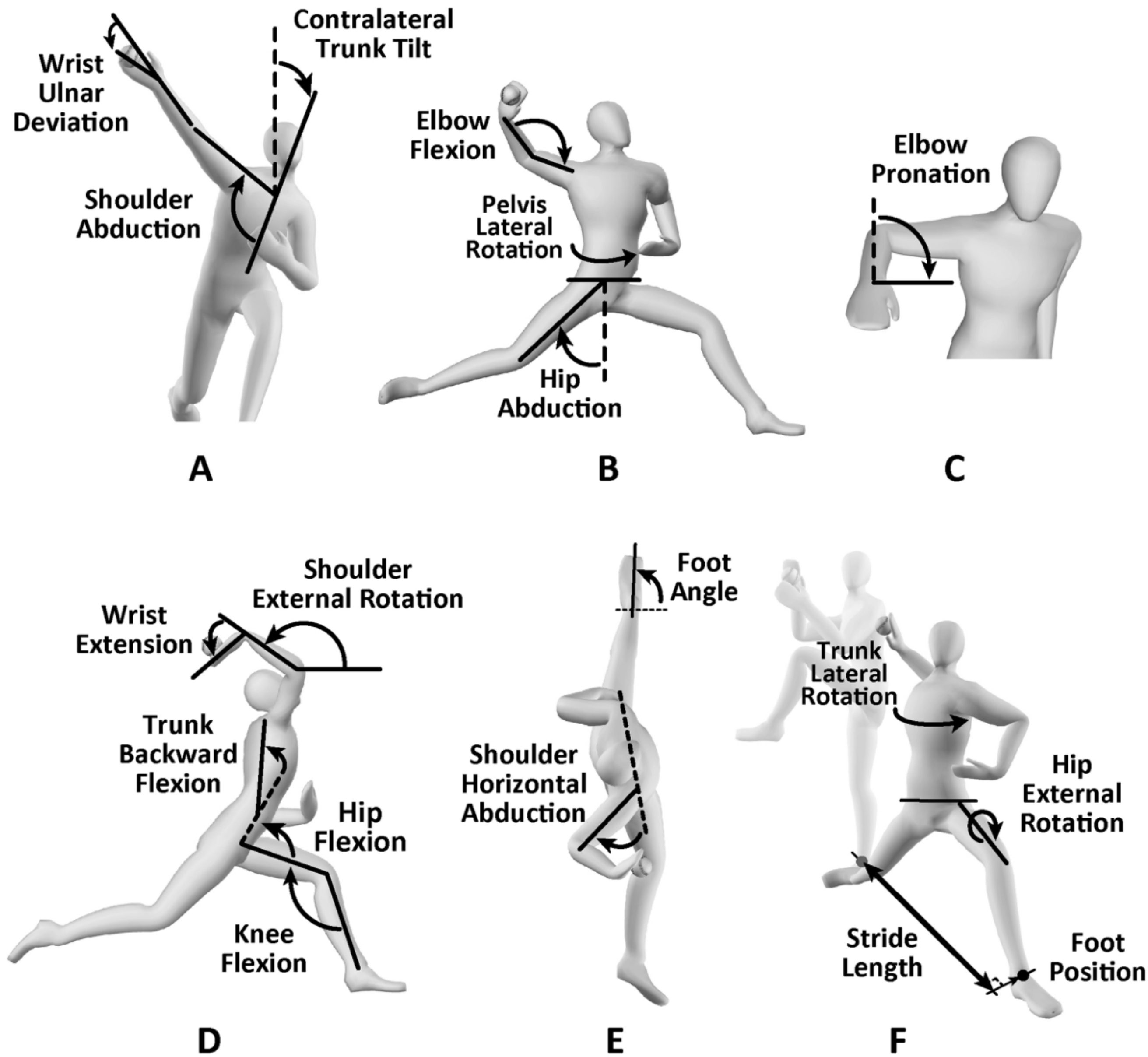

Figure 2. Definitions of kinematic data: (A) wrist ulnar deviation, shoulder abduction, and contralateral trunk tilt; (B) elbow flexion, pelvis lateral rotation, and hip abduction; (C) elbow pronation; (D) shoulder external rotation, wrist extension, trunk backward flexion, hip flexion, and knee flexion; (E) foot angle and shoulder horizontal abduction; and (F) trunk lateral rotation, hip external rotation, stride length, and foot position.

ΔCOM_z; and onset time of trunk rotation. $P < .05$ was considered statistically significant.

RESULTS

The mean peak elbow varus torque across 107 pitchers was 5.0 ± 1.2 %BWH (57.0 ± 15.7 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 ± 5.5 km/h (74.7 ± 5.5 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 ΔCoM_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

TABLE 1
Kinematic Parameters in Peak Elbow Varus Torque on Multiple Regression (N = 107 Pitchers)[a]

Kinematic Variable	Mean ± SD (95% CI)	Coefficient	Standard Coefficient	*P*
At stride foot contact				
Wrist flexion (+) or extension (–)	–35.0 ± 13.5 (–37 to –32)	0.027	0.305	**<.001**
Wrist ulnar (+) or radial (–) deviation	–7.4 ± 8.7 (–9 to –6)	—	—	.687
Elbow flexion	101.3 ± 17.3 (99 to 105)	—	—	.762
Elbow supination (+) or pronation (–)	–5.6 ± 23.1 (–10 to –1)	0.008	0.162	**.042**
Shoulder abduction	85.2 ± 13.3 (83 to 88)	—	—	.235
Shoulder external (+) or internal (–) rotation	75.7 ± 21.3 (72 to 80)	—	—	.051
Shoulder horizontal adduction (+) or abduction (–)	–32.5 ± 12.9 (–35 to –30)	—	—	.893
Knee flexion (toward 0°) on the leading leg	134.0 ± 9.2 (132 to 136)	0.033	0.260	**<.002**
Knee flexion (toward 0°) on the trailing leg	145.6 ± 6.7 (144 to 147)	–0.035	–0.197	**.017**
Trunk backward (+) or forward (–) flexion	8.7 ± 9.7 (7 to 10)	—	—	.894
Trunk lateral (+) or contralateral (–) flexion	–3.9 ± 10.7 (–6 to –2)	—	—	.090
Trunk lateral (+) or contralateral (–) rotation	–22.9 ± 9.5 (–25 to –21)	—	—	.606
Pelvis lateral (+) or contralateral (–) rotation	53.8 ± 10.5 (45 to 50)	—	—	.463
Hip adduction (+) or abduction (–) on the trailing leg	–15.6 ± 8.7 (–17 to –14)	—	—	.091
Hip internal (+) or external (–) rotation on the trailing leg	13.8 ± 8.9 (12 to 15)	—	—	.342
Hip flexion (+) or extension (–) on the trailing leg	–33.2 ± 8.8 (–35 to –32)	—	—	.097
Hip adduction (+) or abduction (–) on the leading leg	–13.1 ± 13.6 (–16 to –10)	—	—	.369
Hip internal (+) or external (–) rotation on the leading leg	–20.0 ± 9.4 (–22 to –18)	—	—	.674
Hip flexion (+) or extension (–) on the leading leg	58.4 ± 7.4 (57 to 60)	—	—	.791
Stride width, %BH	84.1 ± 4.8 (83 to 85)	—	—	.270
Foot position, m	0.1 ± 0.1 (0.1 to 0.15)	—	—	.387
Foot angle	5.3 ± 10.9 (3 to 7)	—	—	.838
At stride phase				
Onset time of trunk rotation before (+) or after (–) SFC, s	0.03 ± 0.02 (0.03 to 0.04)	—	—	.608
ΔCoM_z upward (+) or downward (–), %BH	–19.1 ± 6.3 (–20 to –18)	–0.062	–0.331	**<.001**
ΔCoM_x pitching (+) or second base (–), %BH	48.5 ± 6.4 (47 to 50)	—	—	.679
ΔCoM_y first (+) or third base (–), %BH	–1.2 ± 3.9 (–2 to –0.4)	—	—	.303

[a]Measurements are in degrees unless otherwise specified. Bolded *P* values indicate statistically significant variables. The dashes indicate excluded parameters in the final multiple regression model. %BH, percentage of body height; ΔCOM_x, displacement of whole-body center of mass in the pitching or second-base direction; ΔCOM_y, displacement of whole-body center of mass in the first- or third-base direction; ΔCOM_z, displacement of whole-body center of mass in the upward or downward direction. The regression equation for predicting peak elbow varus torque was as follows:

$$PEVT = 5.379 + (0.027 \times WFE \text{ at SFC}) - (0.062 \times \Delta COM_z \text{ at SP}) + (0.033 \times KFL \text{ at SFC}) - (0.035 \times KFT \text{ at SFC}) + (0.008 \times ESP \text{ at SFC}),$$

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 angle, KFL is the knee flexion angle on the leading leg, KFT is the knee flexion angle on the trailing leg, and ESP is the elbow supination-pronation angle. The constant is statistically significant ($P = .016$).

TABLE 2
Association Between Significant Kinematic Variables in Peak Elbow Varus Torque and Ball Speed With Linear Regression[a]

Kinematic Variable	R^2	*P*
Wrist flexion (+) or extension (–) at SFC, deg	0.0004	.859
ΔCoM_z upward (+) or downward (–) at SP, %BH	0.078	.004
Knee flexion (toward 0°) on the leading leg at SFC, deg	0.116	<.001
Knee flexion (toward 0°) on the trailing leg at SFC, deg	0.008	.377
Elbow supination (+) or pronation (–) at SFC, deg	0.010	.321

[a]%BH, percentage of body height; ΔCOM_z, displacement of whole-body center of mass in the upward or downward direction; SFC, instant of stride foot contact; SP, stride phase.

downward displacement in ΔCoM_z during the stride phase and knee extension on the leading leg at SFC—were mildly associated with increased ball speed (Table 2).

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[46] 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. Aguinaldo 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[40] 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.[18] 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 CoM_z 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[9] reported that a forearm in pronation during the stride phase generated lower 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.[8,20,24,33] Moreover, regarding dynamic stability of the ulnohumeral joint, Otoshi et al[33] 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.[33] However, the results of previous studies on pitching biomechanics indicated that high school baseball pitchers used approximately 31° of wrist extension at SFC.[4,31] The magnitude of elbow varus torque (resisting valgus) at SFC was significantly lower than that in the arm acceleration phase.[16] 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.[39,41,42] 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.[17,23] Matsuo et al[28] 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[38] 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.[22,48] 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 COM_z was found to be associated with increased peak elbow varus torque, it is unclear by what mechanism vertical displacement of the COM_z 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 CoM_z during the stride phase and the increase in peak elbow varus torque. For this, the brachistochrone curve equation[35] can be of assistance in comprehending the patterns and paths of CoM_z 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.

ACKNOWLEDGMENT

We thank the 107 high school baseball pitchers for participating in this project. We also thank Yoshiaki Kanatani, Masahiko Komai, Seiichi Nomura, Takashi Tachibana, Takafumi Mine, Jun Kameda, Koji Tanaka, Yasuyuki Ueda, Masashi Haruna, and Tetsuya Itano at Nobuhara Hospital for their assistance with motion capture testing. Technical advice in motion data capture was also provided by Qualisys Inc. Finally, the authors appreciate the kind advice of Shinichi Yoshiya at Nishinomiya Kaisei Hospital.

REFERENCES

1. Ae M, Tang H, Yokoi T. Estimation of inertial properties of the body segments in Japanese athletes. *Biomechanisms*. 1992;11:23-33.
2. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech*. 2007;23(1):42-51.
3. Aguinaldo AL, Chambers H. Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *Am J Sports Med*. 2009; 37(10):2043-2048.
4. Barrentine SW, Matsuo T, Escamilla RF, Fleisig GS, Andrews JR. Kinematic analysis of the wrist and forearm during baseball pitching. *J Appl Biomech*. 1998;14(1):24-39.
5. Buffi J, Werner K, Kepple T, Murray W. Computing muscle, ligament, and osseous contributions to the elbow varus moment during baseball pitching. *Ann Biomed Eng*. 2015;43(2):404-415.
6. Cain EL Jr, Andrews JR, Dugas JR, et al. Outcome of ulnar collateral ligament reconstruction of the elbow in 1281 athletes: results in 743 athletes with minimum 2-year follow-up. *Am J Sports Med*. 2010; 38(12):2426-2434.
7. Chu Y, Fleisig GS, Simpson KJ, Andrews JR. Biomechanical comparison between elite female and male baseball pitchers. *J Appl Biomech*. 2009;25(1):22-31.
8. Davidson PA, Pink M, Perry J, Job FW. Functional anatomy of the flexor pronator muscle group in relation to the medial collateral ligament of the elbow. *Am J Sports Med*. 1995;23(2):245-250.
9. Davis JT, Limpisvasti O, Fluhme D, et al. The effect of pitching biomechanics on the upper extremity in youth and adolescent baseball pitchers. *Am J Sports Med*. 2009;37(8):1484-1491.
10. Douoguih WA, Dolce DL, Lincoin AE. Early cocking phase mechanics and upper extremity surgery risk in starting professional baseball pitchers. *Orthop J Sports Med*. 2015;3(4):2325967115581594.
11. Dun S, Kingsley D, Fleisig GS, Loftic J, Andrews JR. Biomechanical comparison of the fastball from wind-up and the fastball from stretch in professional baseball pitchers. *Am J Sports Med*. 2008;36(1): 137-141.
12. Erickson BJ, Nwachukwu BU, Rosas S, et al. Trends in medial ulnar collateral ligament reconstruction in the United States: a retrospective review of a large private-payer database from 2007 to 2011. *Am J Sports Med*. 2015;43(7):1770-1774.
13. Escamilla RF, Slowik JS, Diffendaffer AZ, Fleisig GS. Differences among overhand, three-quarter, and sidearm pitching biomechanics in professional baseball players. *J Appl Biomech*. 2018;34(5): 377-385.
14. Fleisig GS. *The Biomechanics of Baseball Pitching*. University of Alabama at Birmingham; 1994.
15. Fleisig GS, Andrews JR, Cutter GR, et al. Risk of serious injury for young baseball pitchers: a 10-year prospective study. *Am J Sports Med*. 2011;39(2):253-257.
16. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanics. *Am J Sports Med*. 1995;23(2):233-239.
17. Fleisig GS, Barrentine SW, Zheng N, Escamilla RF, Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. *J Biomech*. 1999;32(12):1371-1375.
18. Fleisig GS, Diffendaffer AZ, Ivey B, Aune KT. Do baseball pitchers improve mechanics after biomechanical evaluations? *Sports Biomech*. 2018;17(3):314-321.
19. Fleisig GS, Escamilla RF, Andrews JR, Matsuo T, Satterwhite Y, Barrentine SW. Kinematic and kinetic comparison between baseball pitching and football passing. *J Appl Biomech*. 1996;12(2):207-224.
20. Hamilton CD, Glousman RE, Jobe FW, Brault J, Pink M, Perry J. Dynamic stability of the elbow: electromyographic analysis of the flexor pronator group and the extensor group in pitchers with valgus instability. *J Shoulder Elbow Surg*. 1996;5(5):347-354.
21. Han K-J, Kim Y-K, Park J-Y, Oh K-S. The effect of physical characteristics and field position on the shoulder and elbow injuries of 490 baseball players: confirmation of diagnosis by magnetic resonance imaging. *Clin J Sport Med*. 2009;19(4):271-276.
22. Hof AL, Gazendam MGJ, Sinke WE. The condition for dynamic stability. *J Biomech*. 2005;38(1):1-8.
23. Kageyama M, Sugiyama T, Takai Y, Kanehisa H, Maeda A. Kinematic and kinetic profiles of trunk and lower limbs during baseball pitching in collegiate pitchers. *J Sports Sci Med*. 2014;13(4):742-750.
24. Lin F, Kohli N, Perlmutter S, Lim D, Nuber GW, Makhsous M. Muscle contribution to elbow joint valgus stability. *J Shoulder Elbow Surg*. 2007;16(6):795-802.
25. Lyman S, Fleisig GS, Andrews JR, Osinski ED. Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *Am J Sports Med*. 2002;30(4):463-468.
26. Makhni EC, Morrow ZS, Luchetti TJ, et al. Arm pain in youth baseball players: a survey of healthy players. *Am J Sports Med*. 2015;43(1): 41-46.
27. Mapelli A, Zago M, Fusini L, Galante D, Colombo A, Sforza C. Validation of protocol for the estimation of three-dimensional body center of mass kinematics in sport. *Gait Posture*. 2014;39(1):460-465.
28. Matsuo T, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR. Comparison of kinematic and temporal parameters between different pitch velocity groups. *J Appl Biomech*. 2001;17(1):1-13.

29. Meister K. Injuries to the shoulder in the throwing athlete, part one: biomechanics/pathophysiology/classification of injury. *Am J Sports Med*. 2000;28(2):265-275.
30. Nakamizo H, Nakamura Y, Nobuhara K, Yamamoto T. Loss of glenohumeral internal rotation in Little League pitchers: a biomechanical study. *J Shoulder Elbow Surg*. 2008;17(5):795-801.
31. Nissen CW, Westwell M, Ounpuu S, Patel M, Solomito M, Tate J. A biomechanical comparison of the fastball and curveball in adolescent baseball pitchers. *Am J Sports Med*. 2009;37(8):1492-1498.
32. Olsen SJ II, Fleisig GS, Dun S, Loftice J, Andrews JR. Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *Am J Sports Med*. 2006;34(6):905-912.
33. Otoshi K, Kikuchi S, Shishido H, Konno S. Ultrasonographic assessment of the flexor pronator muscles as a dynamic stabilizer of the elbow against valgus force. *Fukushima J Med Sci*. 2014;60(2):123-128.
34. Oyama S, Yu B, Blackburn JT, Padua DA, Li L, Myers JB. Effect of excessive contralateral trunk tilt on pitching biomechanics and performance in high school baseball pitchers. *Am J Sports Med*. 2013; 41(10):2430-2438.
35. Parnovsky AS. Some generalizations of the brachistochrone problem. *Acta Phys Pol*. 1998;93:55-64.
36. Petty DH, Andrews JR, Fleisig GS, Cain EL. Ulnar collateral ligament reconstruction in high school baseball players: clinical results and injury risk factors. *Am J Sports Med*. 2004;32(5):1158-1164.
37. Pieper HG. Humeral torsion in the throwing arm of handball players. *Am J Sports Med*. 1998;26(2):247-253.
38. Ramsey DK, Crotin RL, White S. Effect of stride length on overarm throwing delivery: a linear momentum response. *Hum Mov Sci*. 2014; 38:185-196.
39. Robb AJ, Fleisig G, Wilk K, Macrina L, Bolt B, Pajaczkowski J. Passive ranges of motion of the hips and their relationship with pitching biomechanics and ball velocity in professional baseball pitchers. *Am J Sports Med*. 2010;38(12):2487-2493.
40. Sabick MB, Torry MR, Lawton RL, Hawkins RJ. Valgus torque in youth baseball pitchers: a biomechanical study. *J Shoulder Elbow Surg*. 2004;13(3):349-355.
41. Saito M, Kenmoku T, Kameyama K, et al. Relationship between tightness of the hip joint and elbow pain in adolescent baseball players. *Orthop J Sports Med*. 2014;2(5):2325967114532424.
42. Sakata J, Nakamura E, Suzukawa M, Akaike A, Shimizu K. Physical risk factors for a medial elbow injury in junior baseball players: a prospective cohort study of 353 players. *Am J Sports Med*. 2017; 45(1):135-143.
43. Saper MG, Pierpoint LA, Liu W, Comstock RD, Polousky JD, Andrews JR. Epidemiology of shoulder and elbow injuries among United States high school baseball players: school years 2005-2006 through 2014-2015. *Am J Sports Med*. 2018;46(1):37-43.
44. Takagi Y, Oi T, Tanaka H, et al. Increased horizontal shoulder abduction is associated with an increase in shoulder joint load in baseball pitching. *J Shoulder Elbow Surg*. 2014;23(12):1757-1762.
45. Tanaka H, Toyohiko H, Inui H, et al. Estimation of shoulder behavior from the viewpoint of minimized shoulder joint load in adolescent baseball pitchers. *Am J Sports Med*. 2018;46(12): 3007-3013.
46. Werner SL, Murray TA, Hawkins RJ, Gill TJ. Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. *J Shoulder Elbow Surg*. 2002;11(2):151-155.
47. Winter DA. Anthropometry. In: Winter DA, ed. *Biomechanics and Motor Control of Human Movement*. 4th ed. John Wiley and Sons; 2009.
48. Winter DA. Human balance and posture control during standing and walking. *Gait Posture*. 1995;3(4):193-214.
49. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *J Biomech*. 2002;35(4):543-548.
50. Wu G, van der Helm FC, Veeger HE, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part II: shoulder, elbow, wrist and hand. *J Biomech*. 2005;38(5):981-992.
51. Yang J, Mann BJ, Guettler JH, et al. Risk-prone pitching activities and injuries in youth baseball: findings from a national sample. *Am J Sports Med*. 2014;42(6):1456-1463.