

Role of Rotational Kinematics in Minimizing Elbow Varus Torques for Professional Versus High School Pitchers

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Background: Elbow injury rates among baseball pitchers are rapidly rising. However, this increase has been most dramatic among high school (HS) pitchers.

Purpose: To examine pitch velocity and the kinetic and kinematic characteristics of HS versus professional (PRO) pitchers to identify potential differences that may play a role in the increased risk of ulnar collateral ligament injury in youth pitchers.

Study Design: Controlled laboratory study.

Methods: A total of 37 HS (mean \pm SD: age, 16 ± 1 years) and 40 PRO (age, 21 ± 2 years) baseball pitchers completed maximal-effort baseball pitches during a single testing session, from which pitch velocity (PV), absolute and normalized elbow varus torque (EVT_A and EVT_N , respectively) during arm cocking and at maximum shoulder external rotation (MER), and 8 other elbow and shoulder torques or forces and rotational kinematics of the pelvis and trunk were analyzed, recorded, and compared.

Results: PV was greater in PRO than HS athletes; EVT_A was greater in PRO than HS athletes during arm cocking and at MER; but EVT_N was similar during arm cocking and greater in HS than PRO athletes at MER. In PRO athletes, PV was not related to EVT_A during arm cocking or MER ($r = 0.01-0.05$). Furthermore, in PRO athletes, EVT_A during arm cocking and at MER were inversely related to upper trunk rotation at hand separation and foot contact and to pelvis rotation at elbow extension ($r = -0.30$ to -0.33). In contrast, in HS athletes, PV was strongly related to EVT_A during arm cocking and MER ($r = 0.76-0.77$). Furthermore, in HS athletes, PV and EVT_A during arm cocking and at MER were moderately or strongly related to the other elbow and shoulder torques and forces ($r = 0.424-0.991$), and EVT_A was not related to upper trunk rotation or pelvis rotation throughout the throwing motion ($r = -0.16$ to 0.15).

Conclusion: The kinetic and rotational kinematic differences observed between PRO and HS pitchers in this study may help explain the greater performance of PRO pitchers while allowing them to minimize EVT during pitching. HS pitchers, however, do not appear to be as capable of utilizing the forces generated by rotation of their trunk and pelvis to aid in pitching, and those who throw the hardest generate the greatest forces at the shoulder and elbow. As a result, they experience higher EVTs relative to their body size, which may place them at an increased risk of injury.

Clinical Relevance: HS pitchers throw harder primarily by generating larger forces in the arm and shoulder. Thus, owing to the relative physical immaturity of HS versus PRO pitchers, these factors may place them at an increased risk of injury. Coaches may first wish to focus on improving the rotational kinematics of HS pitchers rather than first focusing on achieving greater pitch velocities.

Keywords: baseball; pitching; biomechanics; motion analysis; pitch velocity

During the pitching motion, a large valgus torque is placed on the elbow as the pelvis and torso rotate toward the target (ie, home plate) and the shoulder rapidly externally rotates just before maximum external rotation.¹⁷ To stabilize the elbow during a throw, this valgus stress is opposed by a varus torque, of which the ulnar collateral ligament

(UCL) is a primary contributor, providing approximately half (54%) of this torque.²² Because the UCL has a failure threshold of approximately 30 to 40 N·m of varus torque and varus torques may routinely exceed 75 to 80 N·m,¹⁷ throwing athletes are especially susceptible to UCL injury.

Recently, much attention has been placed on the rate of UCL injury and reconstructive surgery, commonly known as Tommy John surgery. Indeed, the scientific literature^{2,7,9,10,20,25,31} and the popular press^{5,6,21} are littered with articles that have described this problem and asked

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the question, “What is the cause?” Perhaps most alarming is the rate of UCL injury and reconstruction in youth pitchers, which has been called an “epidemic.”²¹

In a retrospective study of a private-payer database on UCL reconstruction in the United States, Erickson et al¹³ reported that between 2007 and 2011, the average incidence of UCL reconstruction across all ages was 3.96 per 100,000 patients but that the average incidence for 15- to 19-year-olds was 22.0 per 100,000. Furthermore, Erickson et al¹³ reported that there were significantly more (56.8%) UCL procedures performed in 15- to 19-year-olds than any other age group and that the incidence of UCL reconstruction was growing at a rate of 9.1% per year among 15- to 19-year-olds. Therefore, the data presented by Erickson et al¹³ suggest that UCL injury and reconstructive surgery occur at a much higher rate in high school (HS) throwers than any other age group and that the incidence of injury and/or reconstruction is growing at alarming rates.

Proper pitching biomechanics can help pitchers maximize their throwing performance while limiting their risk of injury. Thus, an examination of pitching kinematics, which describes the motion of a body, of pitchers at different levels of baseball may provide important information regarding biomechanical differences that may lead to improved performance and reduced injury risk. Kinetic analyses, on the other hand, study the forces related to movement and may provide information directly related to injury risk. For example, if the UCL is subjected to higher forces, it undergoes greater strain and is at greater risk for injury or failure. Therefore, the purpose of this study was to examine pitch velocity (PV) and the kinetic and kinematic characteristics of HS versus professional (PRO) pitchers to identify potential differences that may play a role in the increased risk of UCL injury for youth pitchers. We hypothesized (1) that PRO pitchers would achieve higher pitch velocities than HS pitchers; (2) that absolute elbow varus torque (EVT_A) would be greater in PRO pitchers but that normalized elbow varus torque (EVT_N) would be greater in HS pitchers; (3) that elbow varus torque (EVT) would be related to PV in PRO and HS pitchers; (4) that pelvis, trunk, and/or upper body rotation would be greater in PRO than HS pitchers; and (5) that these rotational variables would be inversely related to EVT in PRO but not HS pitchers.

METHODS

Participants

Thirty-seven HS pitchers (mean \pm SD: age, 16 \pm 1 years; height, 178 \pm 7 cm; weight, 74 \pm 10 kg) and 40 PRO pitchers (age, 21 \pm 2 years; height, 189 \pm 4 cm; weight, 94 \pm 9 kg)

completed this study. PRO pitchers included pitchers from Minor League Baseball teams affiliated with Major League Baseball (Low-A, High-A, AA, and AAA). Participants were included if they had no record of moderate to severe injury (requiring >2 weeks of rest or rehabilitation) within the past 6 months and had been cleared by their doctor or physical therapist to participate. Prior to testing, each participant completed an informed consent document and a privacy waiver. The Oklahoma State University Institutional Review Board determined that approval (application ED-17-67; board correspondence, June 20, 2017) was not necessary for the analyses or publication of these data, because they were transferred to Oklahoma State University as de-identified data from Motus Global and therefore did not qualify as human subject research as defined in 45 CFR 46.102 (d) and (f).

Procedures

On the day of testing, 46 reflective markers were placed on anatomic landmarks of each participant, which included the bilateral placement on the second metatarsal, posterior calcaneus, lateral and medial malleolus, lateral and medial femoral epicondyle, greater trochanter, anterior and superior iliac spine, lateral tip of the acromion, medial clavicle, lateral and medial humeral epicondyle, radial styloid, and ulnar styloid. Additional markers were placed on T2 and T8 of the thoracic spine, the xyphoid process, the right shank, the right and left forearm, the right and left bicep, the scapulae, and on the distal end of the third metacarpal of the throwing hand. Markers were affixed with tape and hypoallergenic skin adhesive and were secured with an adhesive overlay. The participant was then allowed as much time as he needed to perform a warm-up routine of choice to prepare to throw pitches at maximal effort.¹⁸

Position coordinate data of the reflective markers were collected with an 8-camera, 480-Hz Raptor-E motion analysis system (Motion Analysis Corp). The global coordinate system was established such that the positive *Z* was vertically upward, the positive *X* was perpendicular to *Z* and toward home plate, and *Y* was the cross product of *Z* and *X*. One static calibration trial was collected while the participant stood in the middle of the cameras' capture volume, facing forward with the shoulders abducted to 90° and internally rotated 0°, elbows flexed to 90°, and with his heels against the pitching rubber. The static trial was conducted to align the participant with the laboratory coordinate system as well as to define local coordinate systems. These methods have been used previously and have been reported to have high reliability.⁸

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Ethical approval for this study was waived by the Oklahoma State University–Stillwater Institutional Review Board.

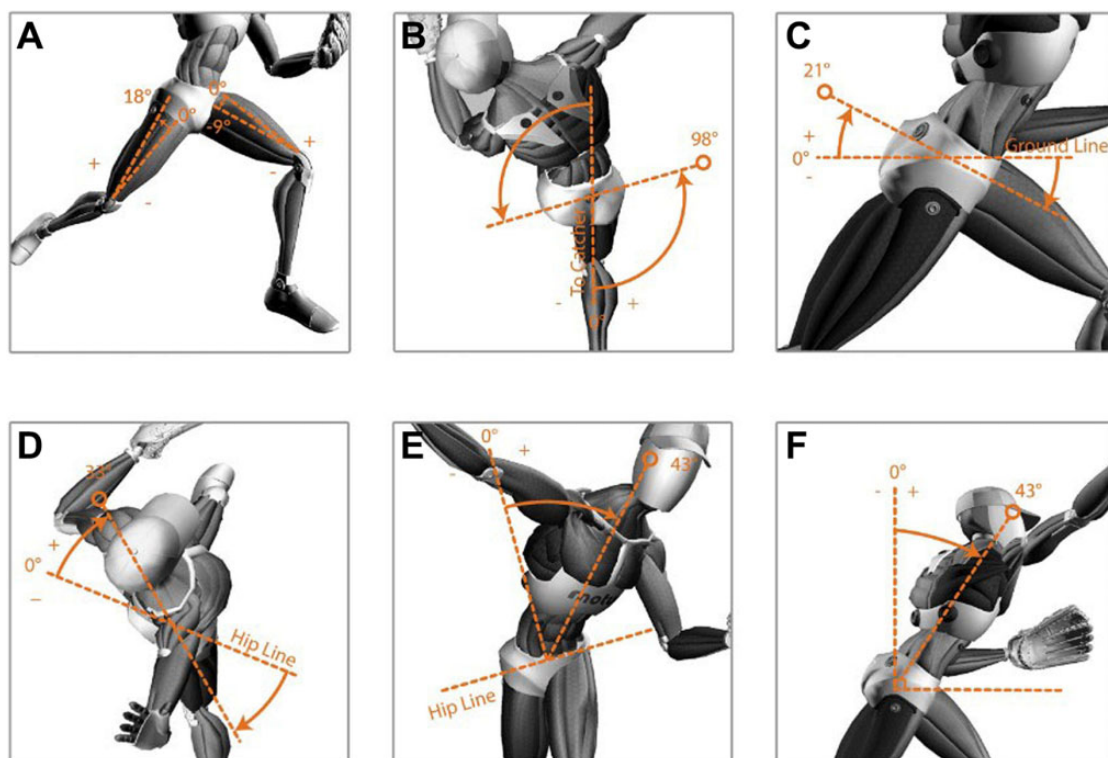


Figure 1. Illustration of the ways in which pelvis and trunk kinematic data were calculated. (A) Lead and back hip rotation, (B) pelvis rotation, (C) pelvis flexion, (D) trunk rotation, (E) trunk lateral flexion, and (F) trunk flexion.

Following the static calibration trial, each participant was tested as described previously.^{14,16,29} Briefly, each pitcher threw 8 fastballs from the windup with game-like effort to a catcher behind home plate positioned 18.4 m (60 ft 6 in), or regulation distance, from the pitching rubber. The participant pitched at his own set pace. PV was calculated with a marker placed on the ball and tracked through the inside of the capture volume. The 5 pitches with the greatest PV were used for analysis.

Data Processing

Marker data were postprocessed with Cortex 6.1 software (Motion Analysis Corp). The raw XYZ coordinates were low-pass filtered with a Butterworth filter and a cutoff frequency of 13.4 Hz.^{14,16} A model was built in Skeleton Builder and Kintools RT (Motion Analysis Corp) to compute relative segment rotations and translations of the upper trunk, pelvis, upper arms, forearms, thighs, shanks, and feet.

Kinematic Data Processing

For each pitch, full body kinematics was calculated to determine the events of pitching. Desired kinematic data were extracted at key frames of the pitch with MATLAB (The MathWorks): maximum knee height (MKH), hand separation (HSP), elbow extension (EE), foot contact (FC), maximum shoulder external rotation (MER), ball

release (BR), and maximum shoulder internal rotation (MIR). MKH was identified as the frame where the stride leg reached maximum vertical displacement in the Z direction. HSP was identified as the frame when the distance between the lead wrist and throwing wrist reached a maximum acceleration between the instances of MKH and FC. EE was identified as the frame when the throwing arm reached maximum EE before the instance of FC. FC was defined as the first frame when the lead toe or heel reached minimum Z. Throwing arm MER was established during the frame in which the throwing arm reached maximum external rotation. BR was determined as the fourth frame after the wrist virtual marker passed the elbow virtual marker in the X direction.¹⁴ Shoulder MIR was identified during the frame when the throwing arm reached maximum internal rotation.

Lead and back hip rotation was calculated as the angle between the pelvis and the femur in the transverse plane and was negative when internally rotated and positive when externally rotated (Figure 1A). Pelvic rotation was defined as 90° when the pelvis was aligned with the global X direction and 0° when the anterior pelvis was facing home plate (global Y) (Figure 1B). Pelvic flexion (tilt) was defined as the anterior rotation of the pelvis, where 0° was the neutral position, forward tilt was measured as positive, and backward was negative (Figure 1C). Upper trunk rotation was defined as the angle between the pelvis and upper trunk in the transverse plane (Figure 1D). Upper trunk

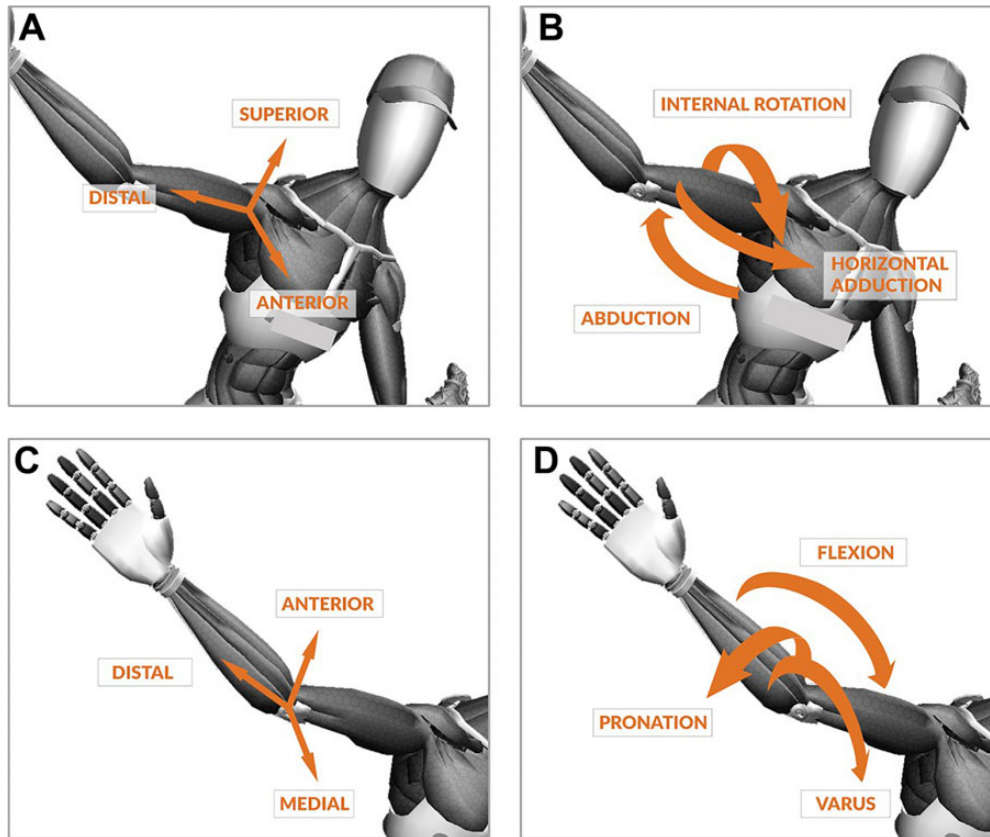


Figure 2. The directions of the force vectors at the (A) shoulder and (C) elbow and the anatomic terms of motion at the (B) shoulder and (D) elbow that were used for kinetic data processing.

lateral flexion was calculated as the angle between the pelvis and upper trunk in the coronal plane and was defined as 0° when the upper trunk line was parallel to the pelvic line and positive when tilted toward the glove (Figure 1E). Upper trunk flexion was calculated as the angle between the superior direction of the upper trunk and the global Z direction in the sagittal plane, where a positive angle reflected forward trunk flexion (Figure 1F). Each dependent variable was averaged across the 5 pitches with the highest velocities and used for analysis.

Elbow and Shoulder Torques

The kinetics for the shoulder and elbow joints during the throwing motion was calculated with methods described by Feltner and Dapena.¹⁵ Values were reported as the force or torque applied by the distal segment onto the proximal segment, similar to previous studies (Figure 2).^{2,28,32} Several maximum values for elbow and shoulder kinetics were identified during key phases of the pitching motion: arm cocking (EVT), elbow medial shear force, shoulder rotation torque and shoulder horizontal abduction torque, arm acceleration (elbow anterior shear force, elbow flexion torque, shoulder anterior shear force), and arm deceleration (elbow proximal force and shoulder proximal force). All

forces and torques were calculated as absolute and normalized values.

Normalized forces were calculated as follows:

$$\text{normalized force} = [\text{absolute force (N)}/\text{body mass (N)}] \times 100.$$

Normalized torques were calculated as follows:

$$\text{normalized torque} = \left\{ \frac{\text{absolute torque (N} \cdot \text{m)}}{[\text{body mass (N)} \times \text{height (m)}]} \right\} \times 100.$$

Statistical Analysis

Data are presented as mean \pm SE unless otherwise noted. Eight separate 2-way mixed factorial analyses of variance (group [PRO vs HS] \times phase [MKH vs HSP vs EE vs FC vs MER vs BR vs MIR]) were used to analyze lead and back hip rotation, pelvis rotation, pelvis flexion (tilt), upper trunk rotation, upper trunk lateral flexion, and upper trunk flexion. In the case of a significant interaction or main effect, follow-up analyses included repeated-measures 1-way analyses of variance, Bonferroni-corrected dependent-samples *t* tests, and independent-samples *t* tests. The mean \pm SE change scores were also calculated and reported to describe the changes in the kinematic variables across phases. In addition, independent-samples *t* tests were used

TABLE 1
Elbow and Shoulder Forces and Torques Between PRO Versus HS Pitchers^a

	Absolute			Normalized		
	PRO	HS	<i>P</i>	PRO	HS	<i>P</i>
Pitch velocity, m/s	38.58 ± 0.99	31.64 ± 2.29	<.001			
Arm cocking						
Elbow varus torque, N·m	86.35 ± 16.23	50.43 ± 17.71	<.001	2.83 ± 0.67	2.91 ± 1.10	<.645
Elbow medial shear force, N	300.73 ± 57.65	186.49 ± 65.73	<.001	32.19 ± 4.72	19.44 ± 4.66	<.001
Shoulder rotation torque, N·m	93.43 ± 16.59	54.26 ± 18.21	<.001	2.99 ± 0.58	3.18 ± 0.68	<.194
Shoulder horizontal abduction torque, N·m	104.54 ± 21.47	63.51 ± 18.73	<.001	3.54 ± 1.13	3.76 ± 0.96	<.375
Maximum external rotation: elbow varus torque, N·m	79.19 ± 14.93	45.10 ± 16.11	<.001	4.48 ± 0.63	5.59 ± 0.81	<.001
Arm acceleration						
Elbow anterior shear force, N	415.11 ± 56.62	243.62 ± 61.78	<.001	44.72 ± 5.39	46.01 ± 9.83	<.481
Elbow flexion torque, N·m	72.39 ± 9.50	39.87 ± 11.35	<.001	7.80 ± 0.90	4.21 ± 0.90	<.001
Shoulder anterior shear force, N	436.76 ± 79.72	278.38 ± 80.52	<.001	46.94 ± 7.38	51.62 ± 10.80	<.031
Arm deceleration						
Elbow proximal force, N	1046.56 ± 115.61	613.05 ± 151.34	<.001	112.66 ± 9.39	64.57 ± 11.70	<.001
Shoulder proximal force, N	1056.95 ± 134.27	612.20 ± 142.68	<.001	113.66 ± 10.37	114.65 ± 20.24	<.790

^aData are reported as mean ± SD. Bolded *P* values indicate a statistically significant difference between groups (*P* < .05). HS, high school; PRO, professional.

to compare PV, EVT_A, and EVT_N during arm cocking and at MER, elbow medial shear force at arm cocking, shoulder rotation torque at arm cocking, shoulder horizontal abduction torque at arm cocking, elbow anterior shear force at arm acceleration, elbow flexion torque at arm acceleration, shoulder anterior shear force at arm acceleration, elbow proximal force at arm deceleration, and shoulder proximal force at arm deceleration between PRO and HS pitchers. Finally, Pearson correlation coefficients were used to analyze relationships among PV, the elbow and shoulder forces and torques of interest, and the kinematic data (ie, hip, pelvis and upper trunk rotation; pelvis and trunk flexion). Pearson correlation coefficients were interpreted per the recommendation of Cohen¹¹ and Hopkins¹⁹ as weak (0.10), moderate (0.30), or strong (0.5). The a priori alpha level was set at .05, and all analyses were completed with SPSS Statistics (v 23; IBM Corp).

RESULTS

Table 1 contains the mean ± SD comparisons for PV and the absolute and normalized elbow and shoulder forces and torques in the PRO versus HS pitchers. Of note, PV was greater in PRO than HS pitchers, EVT_A was greater in PRO than HS pitchers during arm cocking and at MER, but EVT_N was similar during arm cocking and was greater in HS than PRO pitchers at MER. In PRO pitchers, PV was not related to EVT_A during arm cocking (*r* = 0.047) or at MER (*r* = 0.012) but was related to shoulder anterior shear force (*r* = 0.322), elbow flexion torque (*r* = 0.323), and elbow anterior shear force (*r* = 0.367) during arm acceleration. Furthermore, in PRO pitchers, EVT_A during arm cocking and at MER was moderately or strongly related to shoulder anterior shear force, shoulder rotation torque, shoulder proximal force, elbow proximal force, shoulder horizontal abduction torque, elbow medial shear force, and elbow anterior shear force (*r* = 0.387-0.986), but it was inversely

related to upper trunk rotation at HSP (*r* = -0.311 to -0.325) and FC (*r* = -0.313 to -0.324) and to pelvis rotation at EE (*r* = -0.296 to -0.310). In contrast, in HS pitchers, PV was strongly related to EVT_A during arm cocking (*r* = 0.770) and at MER (*r* = 0.761). Furthermore, in HS pitchers, PV and EVT_A during arm cocking and at MER were moderately or strongly related to elbow flexion torque, shoulder anterior shear force, shoulder rotation torque, shoulder proximal force, elbow proximal force, shoulder horizontal abduction torque, elbow medial shear force, and elbow anterior shear force (*r* = 0.424-0.991). Finally, EVT_A was not related to upper trunk rotation or pelvis rotation throughout the throwing motion in HS pitchers (*r* = -0.164 to 0.151).

For upper trunk lateral flexion, upper trunk flexion, pelvis flexion (tilt), and lead hip rotation, there were no phase × group interactions (*P* = .06-.49; partial η^2 = 0.01-0.03) or main effects for group (*P* = .15-.99), but there were main effects for phase (*P* < .001). Upper trunk lateral flexion (collapsed across group) increased from MKH to EE (mean ± SE change = 9.97° ± 1.03°), plateaued from EE to FC (0.43° ± 1.18°), decreased from FC to MER (-37.67° ± 1.33°), plateaued from MER to BR (-1.57° ± 0.75°), and then increased from BR to MIR (4.37° ± 0.57°). Upper trunk flexion decreased from MKH to HSP (-14.48° ± 1.08°), plateaued from HSP to EE (0.77° ± 0.65°), decreased from EE to MER (-37.20° ± 1.58°), and then increased from MER to MIR (34.53° ± 1.01°). Pelvis tilt increased from MKH to EE (23.51° ± 1.09°) and plateaued from EE to FC (2.59° ± 0.92°) before increasing again from FC to MIR (23.97° ± 1.18°). Lead hip rotation decreased from MKH to HST (-7.96° ± 1.16°), plateaued from HST to EE (1.26° ± 0.87°), increased from EE to FC (7.94° ± 1.42°), decreased from FC to MER (-10.69° ± 1.30°), increased from MER to BR (3.13° ± 0.61°), and then plateaued again from BR to MIR (1.24° ± 0.55°).

For upper trunk rotation (Figure 3), there was no phase × group interaction (*P* = .41; partial η^2 = 0.01). However,

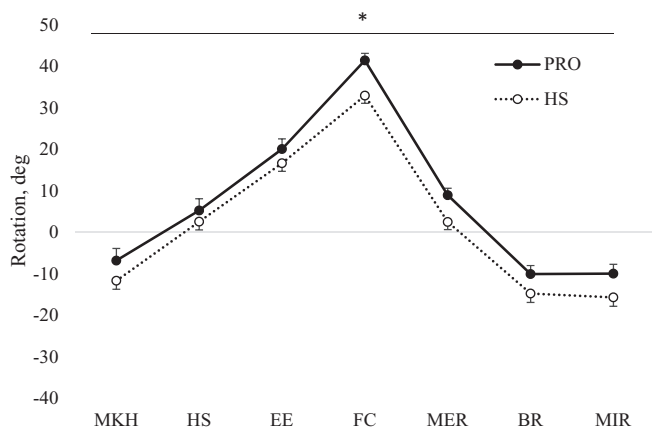


Figure 3. Upper trunk rotation at maximum knee height (MKH), hand separation (HSP), elbow extension (EE), foot contact (FC), maximum shoulder external rotation (MER), ball release (BR), and maximum shoulder internal rotation (MIR) for professional (PRO) and high school (HS) pitchers. Values are presented as mean \pm SE. *Significant main effect for group across all phases (PRO > HS; $P < .05$).

there was a main effect for phase ($P < .001$) and group ($P = .04$). When collapsed across group, there was an increase from MKH to FC ($46.50^\circ \pm 1.64^\circ$), a decrease from FC to BR ($-18.18^\circ \pm 0.79^\circ$), and then a plateau from BR to MIR ($-0.39^\circ \pm 0.72^\circ$). When collapsed across phase, upper trunk rotation was significantly greater in PRO ($6.97^\circ \pm 1.72^\circ$) than HS ($1.79^\circ \pm 1.79^\circ$) pitchers.

For pelvis rotation (Figure 4) and back hip rotation (Figure 5), there were phase \times group interactions ($P \leq 0.01$; partial $\eta^2 = 0.05$ - 0.06). Post hoc analyses revealed that pelvis rotation was significantly greater in PRO than HS pitchers for MKH ($124.65^\circ \pm 10.78^\circ$ vs $119.03^\circ \pm 13.44^\circ$; $P = .046$) and HSP ($118.12^\circ \pm 11.54^\circ$ vs $109.68^\circ \pm 14.73^\circ$; $P = .006$). In PRO pitchers, pelvis rotation decreased from MKH to BR ($-133.44^\circ \pm 1.95^\circ$), then plateaued from BR to MIR ($-0.56^\circ \pm 0.47^\circ$). In HS pitchers, pelvis rotation decreased from MKH to MIR ($-128.04^\circ \pm 2.09^\circ$). Furthermore, back hip rotation was significantly lower (but greater in magnitude, as indicated by the mean distance from 0°) in PRO than HS pitchers for MKH ($-15.30^\circ \pm 10.55^\circ$ vs $-7.34^\circ \pm 8.40^\circ$; $P \leq 0.001$) and HSP ($-23.04^\circ \pm 10.32^\circ$ vs $-15.80^\circ \pm 10.52^\circ$; $P = .003$). In PRO pitchers, back hip rotation decreased from MKH to EE ($-11.23^\circ \pm 1.61^\circ$), increased from EE to MER ($44.63^\circ \pm 2.24^\circ$), then plateaued from MER to BR ($-0.22^\circ \pm 0.92^\circ$) and decreased from BR to MIR ($-2.49^\circ \pm 0.74^\circ$). In HS pitchers, back hip rotation decreased from MKH to EE ($-15.7^\circ \pm 1.37^\circ$), increased from EE to MER ($39.37^\circ \pm 2.51^\circ$), and then plateaued from MER to MIR ($-0.62^\circ \pm 1.68^\circ$).

DISCUSSION

The results of the present study indicated that PRO pitchers achieve higher fastball velocities and EVT_A than HS pitchers (see Table 1). However, when torques were

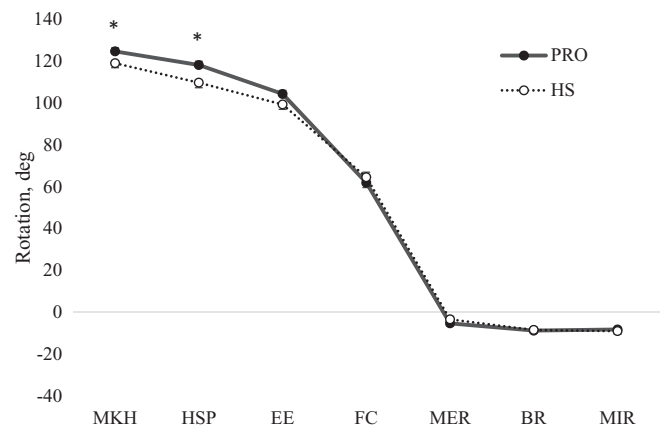


Figure 4. Pelvis rotation at maximum knee height (MKH), hand separation (HSP), elbow extension (EE), foot contact (FC), maximum shoulder external rotation (MER), ball release (BR), and maximum shoulder internal rotation (MIR) for professional (PRO) and high school (HS) pitchers. Values are presented as mean \pm SE. *Significant difference between PRO and HS (PRO > HS; $P < .05$).

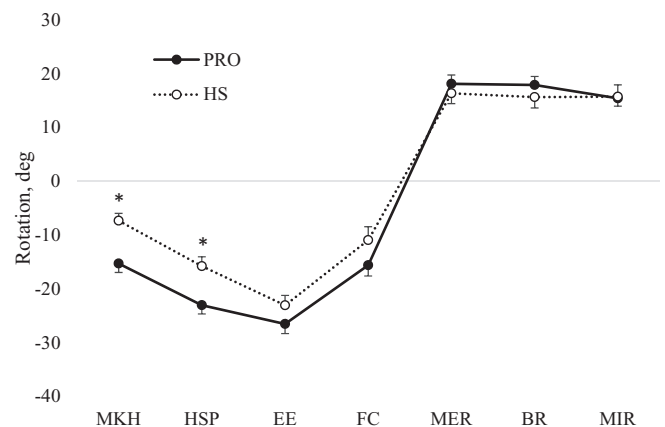


Figure 5. Back hip rotation at maximum knee height (MKH), hand separation (HSP), elbow extension (EE), foot contact (FC), maximum shoulder external rotation (MER), ball release (BR), and maximum shoulder internal rotation (MIR) for professional (PRO) and high school (HS) pitchers. Values are presented as mean \pm SE. *Significant difference between PRO and HS (PRO > HS; $P < .05$).

normalized, EVT was not different at arm cocking but was greater in HS than PRO pitchers at MER. Moreover, PRO pitchers demonstrated a greater degree of pelvis and back hip rotation at MKH and HSP (Figures 4 and 5, respectively) and greater upper trunk rotation across all phases than HS pitchers (Figure 3). Interestingly, in HS but not PRO pitchers, PV was related to EVT_A at arm cocking ($r = 0.770$) and MER ($r = 0.761$) and several other torques and forces at the shoulder and elbow. Furthermore, we observed significant inverse relationships between EVT_A and upper trunk rotation at HSP and FC and pelvis rotation at EE in PRO but not HS pitchers. Together, our results suggest

that although PRO pitchers experience greater EVT_A than HS pitchers, they generate greater rotation in the pelvis and trunk, which may ultimately allow them to generate greater fastball velocities. In contrast, the HS pitchers who threw the hardest experienced greater elbow and shoulder torques. Furthermore, the greater EVT_N experienced by the HS pitchers at MER suggests that they may be at increased injury risk because the varus loads placed on the elbow are higher relative to their body size and/or physical maturity compared with PRO pitchers. These data may have important implications for youth baseball players, who may often compete for ≥ 8 consecutive months, playing ≥ 70 games per calendar year.²⁷

Proper development of pitching mechanics is important not only for performance (ie, achieving high PVs) but also for limiting the risk of throwing-related injuries. As pitchers mature, the forces and torques sustained throughout the entire kinetic chain increase, as does the ability to achieve higher PVs.^{7,17,30,32} In the present study, PRO pitchers produced higher PV and greater EVT_A than HS pitchers. However, in HS pitchers only, PV was strongly related to EVT_A , and PV and EVT_A were moderately to strongly ($r = 0.424-0.991$) related to elbow flexion torque, shoulder anterior shear force, shoulder rotation torque, shoulder proximal force, elbow proximal force, shoulder horizontal abduction torque, elbow medial shear force, and elbow anterior shear force. Recently, relationships between PV and joint kinetics of the elbow and shoulder have been reported among various levels of baseball pitchers.^{7,20,23,26,32} For example, Post et al²⁶ reported no significant association between PV and elbow valgus torque or shoulder external rotation torque in collegiate baseball pitchers. Hurd et al²⁰ observed a strong positive association in PV and peak elbow adduction moment in uninjured HS baseball pitchers. Therefore, our data support and expand the findings of these previous studies^{20,26} and suggest that PV is strongly related to EVT_A in youth (ie, HS) but not high-level adult pitchers (ie, collegiate and PRO).

Despite the greater EVT_A experienced by PRO pitchers, EVT_N was not different at arm cocking and was greater at MER in HS pitchers. Thus, the greater EVT_A experienced by the PRO pitchers may simply have been a function of their greater body stature (ie, height and weight). However, the fact that HS pitchers experienced greater EVT at MER relative to their body size may have important implications for injury risk in this population. Specifically, HS pitchers experience significant loads on the UCL, perhaps without the requisite physical maturity necessary to handle such loads. Several studies have reported that the thickness of the UCL increases as pitchers age.^{3,4,10} It has also been suggested that sufficient development or strength of the musculature surrounding the elbow may help to alleviate some of the stress placed directly on the UCL during throwing.¹⁷ Therefore, the EVTs and relative physical immaturity of the HS pitchers may lead to an increased risk of injury and may be at least partly responsible for the fact that the number of UCL reconstruction (ie, Tommy John) operations completed per calendar year is greatest in 15- to 19-year-olds and that the rate of UCL reconstruction in these age groups is increasing by

approximately 9% per year,¹² while many of these pitchers will never make it to the PRO level.

Highly skilled throwers demonstrate the ability to optimally coordinate body segments and systematically generate and transfer energy up the kinetic chain.³⁰ For example, it appears that elite pitchers (vs youth pitchers) are better able to generate forces in the larger distal extremities and more effectively transfer these forces up the kinetic chain via pelvis or trunk rotation, resulting in reduced shoulder and elbow torques and perhaps great pitching performance.^{1,24} Thus, we hypothesized that there may be differences in the degree of pelvis and trunk rotation that may help to explain differences in PVs and in the EVTs experienced by PRO versus HS pitchers. Indeed, in the present study, PRO pitchers achieved greater pelvis rotation and back hip rotation at MKH and HSP and greater upper trunk rotation across the pitching motion than HS pitchers. Moreover, although we did not measure rotational velocities in the present study, the fact that pelvis and back hip rotation were greater early on in the pitching motion but similar later in the pitching motion for the PRO versus HS pitchers may suggest that PRO pitchers also achieved greater peak rotational velocities than HS pitchers. Furthermore, upper trunk rotation at HSP and FC and pelvis rotation at EE were inversely associated with EVT_A in the PRO but not HS pitchers. Therefore, our data suggest that the transfer of momentum up the kinetic chain during the throwing motion via pelvis, back hip, and trunk rotation may play an important role in limiting the torque imposed on the UCL (ie, normalized EVT) while generating higher PVs, and it appears that PRO pitchers are better able to accomplish this than HS pitchers. It is possible, then, that improving rotational kinematics in HS pitchers may increase PV and help protect the elbow, but future studies are needed to test this hypothesis.

This study is not without several limitations. First, it is possible that there is a selection bias between groups, as many HS pitchers may never develop the mechanics or physical ability to be a PRO pitcher. Given the cross-sectional nature of this study, our conclusions are based on between-group differences and relationships among variables within groups. Therefore, future longitudinal studies are needed to examine cause-and-effect relationships among the variables studied herein. Finally, it is not clear from this study what preventative measures may be taken. We suggest, however, several plausible options, such as coaching that focuses on the biomechanics of pitching, strength training, and proactive pitching load monitoring and modification. Future studies are warranted to test these hypotheses.

CONCLUSION

The kinetic and rotational kinematic differences observed between PRO and HS pitchers in this study may help explain the greater performance of PRO pitchers while allowing them to minimize EVT, relative to body size, during pitching. HS pitchers, do not generate as much rotation as PRO pitchers and are not as capable of utilizing rotation

to transfer forces up the kinetic chain while pitching. Thus, the HS pitchers who threw the hardest experienced the highest forces at the elbow (ie, EVT) and shoulder. That is, the HS pitchers threw harder primarily by generating larger forces in the arm and shoulder. Furthermore, compared with PRO pitchers, HS pitchers experienced higher EVTs relative to their body size. Thus, owing to the relative physical immaturity of HS versus PRO pitchers, these factors may place them at an increased risk of injury and, in addition to the high volumes of pitching performed by today's youth athlete, could help explain the burgeoning rates of UCL injury in HS pitchers.

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