Correlation of Torque and Elbow Injury in Professional Baseball Pitchers

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Background: During the pitching motion, velocity is generated by the upper extremity kinetic chain on internal rotation of the shoulder and trunk translational/rotational motion. This generation of power places significant forces and torques on the elbow and shoulder. Elbow valgus torque and shoulder rotational torque are theoretically linked to elbow injury.

Hypothesis: Pitchers experiencing higher levels of elbow valgus torque and shoulder external rotation torque throughout the pitching motion are more likely to suffer elbow injury than pitchers with lower levels of torque.

Study Design: Cohort study; Level of evidence, 3.

Methods: With an established biomechanical analysis model, 23 professional baseball pitchers were videotaped during spring training games and followed prospectively for the next 3 seasons for elbow injury. A mixed statistical model using differences of least squares means and analysis of variance was used to analyze the association between elbow injury and torque levels throughout the pitching motion as well as at each major event within the pitching motion.

Results: There were overall statistical trends relating elbow injury with both higher elbow valgus torque ($P = .0547$) and higher shoulder external rotation torque ($P = .0548$) throughout the entire pitching motion. More importantly, there was an individual significant correlation of elbow injury with both higher elbow valgus torque ($P = .0130$) and higher shoulder external rotation torque ($P = .0018$) at the late cocking phase (pitching event of maximum external rotation of the shoulder).

Conclusion: This study provides information that supports existing theories about how and why certain injuries occur during the throwing motion in baseball. The late cocking phase appears to be the critical point in the pitching motion, where higher levels of torque at the shoulder and elbow can result in increased risk of injury. Manipulation of pitching mechanics to alter these torque levels or using these measures to identify pitchers at risk may help decrease injury rates.

Keywords: elbow; shoulder; valgus; rotatory; torque; pitching

Injuries of the throwing arm, especially injuries to the shoulder and elbow, are common in the overhead pitching motion of baseball. Historically, it has been reported that as many as 50% of professional pitchers will experience shoulder or elbow pain that prohibits throwing at some point in their career.[21] Recent epidemiologic studies have suggested that one quarter of all youth pitchers will report elbow pain through 2 seasons of use, and half will report shoulder or elbow pain through the course of 1 season.[12,13] Major League Baseball pitchers are especially prone to injury because of the velocity at which they throw and the repetitive nature of their profession.

The pitching motion is a complex compilation of motion at the trunk, shoulder, and elbow that has effects on the entire upper extremity kinetic chain. Biomechanical studies have thoroughly investigated the angles, velocities, forces, and torques that are present at the elbow and shoulder during the pitching motion.[††] Subtle differences in mechanics (eg, onset of trunk rotation, maximal shoulder external rotation, elbow flexion at ball release) have been shown to produce differences in the torques and forces experienced at the elbow and shoulder throughout the pitching motion.[1,23,25]

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The authors declared that they had no conflicts of interests in their authorship and publication of this contribution.

††References 4, 6, 8, 9, 12, 14, 17-20, 22-25.

The American Journal of Sports Medicine, Vol. 38, No. 7
DOI: 10.1177/0363546510363402

A recurring injury pattern seen within overhead pitchers is elbow valgus (EV) overload syndrome, wherein the structures of the elbow are injured due to tensile force on the medial compartment and compressive force on the lateral compartment.[1,8,25,26] Tension in the medial compartment can produce strain or disruption of the ulnar collateral ligament, and compression in the lateral compartment can produce degenerative chondral changes to the radius and capitellum. This scenario occurs when the elbow cannot create adequate oppositional varus torque to the compression/tension valgus torque generated during the pitching motion. Elbow valgus torque has been theorized as the deforming torque in this injury scenario. For this reason, the kinetics behind EV torque have been evaluated and the magnitude quantified in efforts to learn what mechanics place a pitcher at risk for injury.[1,8,22,25] Shoulder rotational torque has also been noted to be of interest as it has direct theoretic effect on EV torque.[1,8,25] We theorized that pitchers who acquire ball velocity by increased speed of shoulder rotation put a higher stress on the entire kinetic chain. Because this increased speed is acquired through increased rotational torque generated at the shoulder girdle, we believe that shoulder external rotation (SER) torque is a direct quantification of the potentially injurious energy created within the kinetic chain. We therefore see increased magnitudes of SER as a theoretic contributor to risk of injury at the elbow and a theoretic means of measuring the magnitude of the "whipping action" that has been identified as a dangerous style of ball delivery.[1,25]

Previous studies have documented well the relation of kinematics and the magnitude of torques. To our knowledge, however, no study has directly correlated levels of EV torque and SER torque with the incidence of injury in the professional baseball pitcher population. Our goal was to test the established hypothesis that increased EV torque is associated with increased injury as well as our second hypothesis that increased SER torque is associated with increased injury. Correlation was sought throughout the pitching motion and at each major pitching event within the pitching cycle.

MATERIALS AND METHODS

With use of an established model of biomechanical analysis,[17-19] 25 professional pitchers were videotaped by 3 high-speed video cameras during game situations of the 1998 Cactus League season in Arizona. Three 120-Hz video cameras (Peak Performance Technologies, Englewood, Colorado) were set to capture front and dominant-sided views of the throwers (ie, from the left-field side for a right-handed pitcher and from the right-field side for a left-handed pitcher). One camera was set above and behind home plate in the press box and 2 additional cameras were set in the right and left field bleachers. Data were used from the camera set behind home plate and from the appropriate-sided camera recording a given pitcher from his dominant side. The cameras were calibrated with regard to pitching area by simultaneous videotaping of a 24-point calibration frame (Peak Performance Technologies). Markers were placed on the pitching mound to create a reference frame.

Demographic data were collected for each pitcher at the time of biomechanical data collection. The mean age of the pitchers was 26.2 ± 2.92 years (range, 20-30). There were 21 right-handed pitchers and 4 left-handed pitchers. Pitches were thrown from a standard major league mound (10 inches in height) to home plate, a distance of 60 feet 6 inches. Regulation baseballs with a mass of 5 oz and circumference of 9 inches were used. Data for each pitcher were used from the fastest pitch thrown for a strike.

Twenty anatomical landmarks and ball position were manually digitized in each of the camera views using the Peak Performance Motus system. To capture the entire pitching cycle, this process was performed from 50 milliseconds before the ball left the glove to 500 milliseconds after the ball was released. Three-dimensional coordinate data for each anatomical landmark and the ball were produced using the direct linear transformation method. A Butterworth fourth order, zero-lag digital filter was used to condition the data with a cutoff of 10 Hz. Torques and forces were defined at the shoulder and elbow with an established 3-dimensional coordinate system (Figures 1 and 2)[17-19] and calculated according to the methods of Feltner and Dapena.[7]

In the literature, the pitching sequence has been defined with 4 specific pitching events that aid in kinematic analysis. These points include the following pitching events: stride foot contact, maximum shoulder external rotation, the instant of ball release, and the event of maximal internal rotation of the shoulder (Figure 3). Temporally, these events signify the transition between the 3 main phases of the pitching cycle and enable standardized comparison of pitching events and pitchers. The cocking phase represents the period between stride foot contact and maximum shoulder external rotation, the acceleration phase represents the period between maximum shoulder external rotation and the instant of ball release, and the follow-through phase represents the period between the instant of ball release and maximal internal rotation of the shoulder (Figure 3). Temporal normalization required stride foot contact to represent time elapse of 40%, maximum shoulder external rotation to represent time elapse of 80%, the instant of ball release to represent time elapse of 90%, and maximal internal rotation of the shoulder to represent time elapse of 100% (Figure 3). This protocol facilitated comparison among players and calculation of mean values.

For each pitcher, performance data were gathered using www.baseball-reference.com for the years of 1998, 1999, and 2000. Two pitchers who had never pitched in a regular season Major League game after data collection were excluded from the final analysis group, leaving a total of 23 pitchers in the final cohort. Additional confounding factors possibly contributing to injury were also analyzed, including demographic information (age, height, weight, body mass index), pitcher type (starter/reliever), games played, innings pitched, pitches per game, and overall pitch count.

The official Major League Baseball Disabled List injury report for each respective year was used to determine injury data for a given pitcher, including type of injury

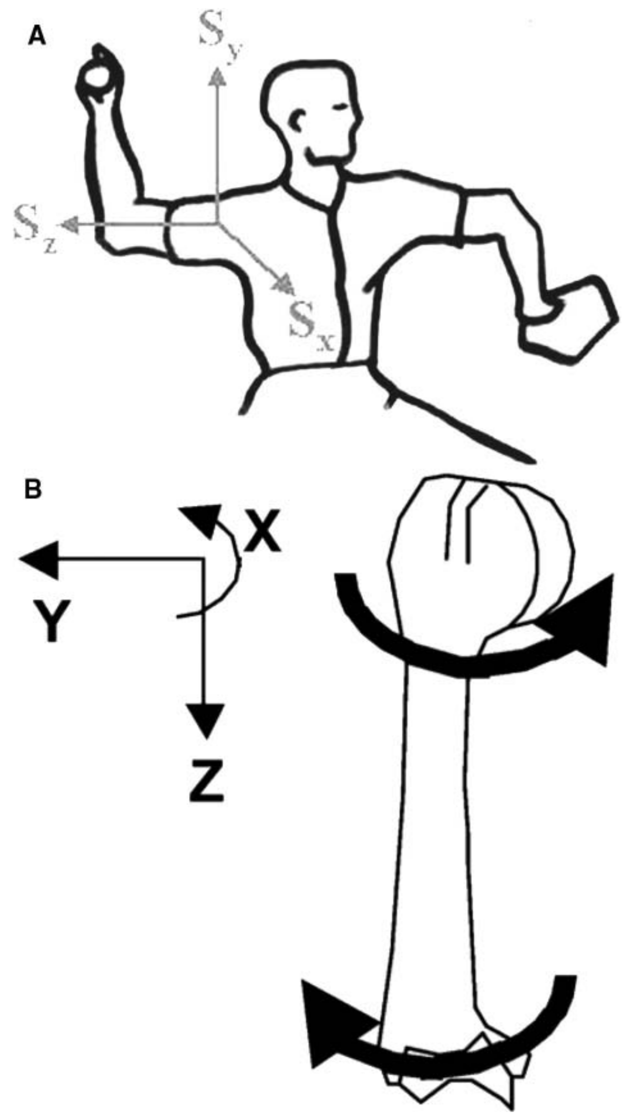

Figure 1. Shoulder definitions. Definition of local coordinate systems at the shoulder (A) and definition of shoulder rotational torque vectors (B). (Figures reproduced from Sabick et al.[18])

and time missed. In pitchers whose injuries involved a surgery, information was obtained via communication with the training staff and/or treating physicians as needed. Injuries not directly related to the elbow were excluded: groin cellulitis, gout, strained calf, hand/wrist injuries, shoulder injuries, and spinal injuries.

Data Analysis

A repeated-measures mixed models analysis of variance with compound symmetry assumptions for within-person variability was used to compare the association of elbow injury with EV and SER torque levels. Additionally, at each major point within the pitching motion, difference between the injured and noninjured groups was analyzed with a differences of least squares means model. An unpaired Student *t* test was used to compare demographic data, performance information, EV torque, and SER torque between the injured and noninjured groups. Statistical significance was defined a priori as $P < .0500$.

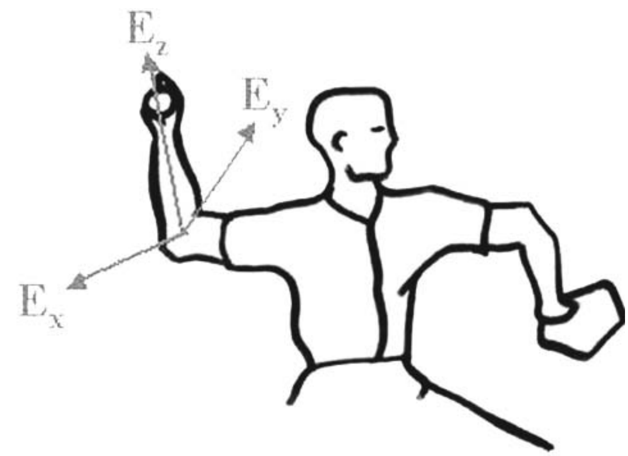

Figure 2. Elbow definitions. Definition of local coordinate systems at the elbow. Ey, valgus torque. (Figures reproduced from Sabick et al.[18])

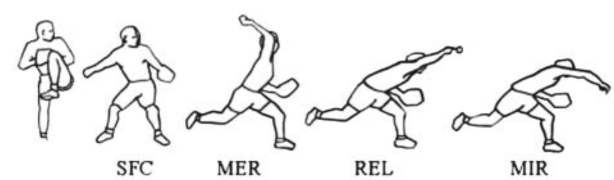

Figure 3. The 4 events of the pitching cycle. For purposes of this analysis, the distinct events of the pitching cycle include stride foot contact (SFC), shoulder maximum external rotation (MER), ball release (REL), and shoulder maximum internal rotation (MIR). (Figures reproduced from Sabick et al.[18])

RESULTS

There were 9 players with elbow injuries in the group of pitchers studied, including 4 pitchers with an elbow muscle strain and/or joint inflammation treated with rehabilitation, 2 pitchers with an ulnar collateral ligament sprain treated with rehabilitation, and 3 pitchers with ulnar collateral ligament tears requiring surgical reconstruction. Demographic and performance data of the injured group were compared with the group of 14 noninjured pitchers, with no statistically significant differences noted (Tables 1 and 2). Differences between maximum EV and maximum SER torque regardless of time were also evaluated with a Student *t* test. No statistical difference was found between the injured and noninjured group involving these 2 values (Table 3).

Using mixed-model analysis, comparison of EV torque throughout the pitching motion found a near-significant statistical trend between the injured and noninjured groups ($P = .0547$) (Figure 4). Further analysis with

TABLE 1
Demographics of Injured Group[a]

Pitcher No.	Age, y	Ht, in	Wt, lb	BMI	R/L	St/Re	Games Played	Innings Pitched	Total Pitches	Pitches/Game	Injury	Treatment
1	24	74	175	22.52	R	Re	54	72.1	1261	23.4	Strain	Rehab
2	25	75	205	25.68	R	Re	181	222	3722	20.6	UCLS	Rehab
3	29	77	190	22.58	R	St	18	95	1489	82.7	Strain/ Inflam	Rehab
4	28	73	192	25.38	L	St	83	446.2	7369	88.8	Strain	Rehab
5	23	74	200	25.73	R	St	20	110	1784	89.2	UCLS	Rehab
6	30	73	236	31.20	R	Re	158	165	2672	16.9	Inflam	Rehab
7	26	73	180	23.80	R	Re	61	227.2	4112	67.4	UCLT	Surgery
8	28	74	200	25.73	R	Re	169	188.2	2955	17.5	UCLT	Surgery
9	20	77	225	26.74	R	St	49	303.2	5200	106.1	UCLT	Surgery
Avg	25.9	74.4	200.3	25.5	1 L/8 R	4 St/5 Re	88.1	203.2	3396.0	56.9		

[a]Demographic data obtained at the time of velocity measurement. Workload data obtained over the following 3 seasons (1998-2000). BMI, body mass index; R, right-handed; L, left-handed; St, starter; Re, reliever; Strain, strain of 1 or more of the muscles at the elbow; Rehab, nonoperative treatment with a focused elbow rehabilitation program; UCLS, ulnar collateral ligament sprain; Inflam, inflammation of the elbow joint; UCLT, ulnar collateral ligament tear; Surgery, ulnar collateral ligament reconstruction.

TABLE 2
Demographics of Noninjured Group With *P* Values of Student *t* Test[a]

Pitcher No.	Age, y	Ht, in	Wt, lb	BMI	R/L	St/Re	Games Played	Innings Pitched	Total Pitches	Pitches/Game
1	30	74	200	25.73	R	Re	148	170.5	2871	19.4
2	23	76	225	27.45	R	St	105	498.1	7565	72.0
3	30	72	180	24.46	R	Re	202	238	3970	19.7
4	23	79	200	22.58	R	Re	12	21	319	26.6
5	30	77	198	23.53	R	St	102	653.1	10 385	101.8
6	26	72	170	23.10	R	St	62	119.5	1966	31.7
7	27	74	213	27.40	R	St	31	77.2	1349	43.5
8	26	74	195	25.09	R	Re	6	7.2	168	28.0
9	26	77	205	24.36	R	Re	7	7	120	17.1
10	30	74	210	27.02	R	Re	61	185.2	3227	52.9
11	26	72	175	23.78	L	St	76	275.1	4701	61.9
12	25	73	155	20.49	R	Re	7	8	165	23.6
13	30	71	160	22.36	R	Re	191	270	4486	23.5
14	28	75	205	25.68	L	Re	108	165.4	3105	28.8
Avg	27.1	74.3	192.2	24.5	2 L/12R	5 St/9 Re	79.9	192.5	3171.2	39.3
P values	.31	.86	.36	.32			.77	.88	.84	.18

[a]*P* values represent statistical significance analysis between injured and noninjured group data based on unpaired Student *t* test analysis. BMI, body mass index; R, right-handed; L, left-handed; St, starter; Re, reliever.

differences of least squares means determined that a statistically significant difference occurred only at the event of maximum external rotation (P = .0130). At the other events, a statistically significant difference of EV torque did not occur. At maximum external rotation, the noninjured group had a mean EV torque of 74.70 N·m (±22.38) and the injured group had a mean EV torque of 91.62 N·m (±22.96) (Table 4).

Using mixed-model analysis, comparison of SER torque throughout the pitching motion found a near-significant statistical trend between the injured and noninjured groups (P = .0548) (Figure 5). Further analysis with differences of least squares means determined that a statistically significant difference occurred only at the event of maximum external rotation (P = .0018). At the other 3 time points, a statistically significant difference of SER torque did not occur. At the event of maximum external rotation, the noninjured group had a mean SER torque of 70.96 N·m (±24.45) and the injury group had a mean SER torque of 89.83 N·m (±23.99) (Table 5).

DISCUSSION

The motion of pitching a baseball is a complex cycle in which the kinetic chain—beginning in the lower extremities and passing through the core, torso, shoulder, elbow, wrist, and hand to the baseball—generates significant forces required to produce high ball velocities. In professional pitchers, velocities are routinely seen approaching, and even exceeding, 100 mph. High levels of energy pass through the components of the kinetic chain to create

TABLE 3
Comparison of Maximum Elbow Valgus Torque and Maximum Shoulder External Rotational Torque Between Injured and Noninjured Groups with Student *t* Test

Torque	Injured (n = 14) Mean (SD)	Noninjured (n = 9) Mean (SD)	*P* Value[a]
Maximum elbow valgus	98.8 (18.8)	91.4 (13.6)	.28
Maximum shoulder external rotational	97.0 (19.1)	88.7 (14.0)	.24

[a]*P* value obtained on Student *t* test analysis.

TABLE 4
Comparison of Elbow Valgus Torque[a]

Pitch Cycle Event	Injured Group Mean Torque, N·m (SD)	Noninjured Group Mean Torque, N·m (SD)	Least Squared Means *P* Value
SFC	2.86 (7.84)	1.97 (7.67)	.89
MER	91.6 (23.0)	74.7 (22.4)	.013
REL	17.2 (14.5)	6.67 (16.3)	.12
MIR	−2.77 (8.62)	0.77 (13.8)	.60

[a]At the 4 major points of the pitching cycle, comparison between injured and noninjured groups of mean elbow valgus torque values produced least squared means analysis with *P* values significant only at maximum shoulder external rotation (MER). SFC, stride foot contact; REL, ball release; MIR, maximal internal rotation.

such a level of ball speed. The overuse injuries commonly seen in pitchers have long been attributed to the effects of these high levels of energy on the weakest links of the kinetic chain, particularly the elbow. In the professional population, however, no study has directly illustrated a link between injury and these high levels of energy.

Our study sought to analyze 2 distinct variables within the complex biomechanics of the pitching cycle—EV torque and SER torque—as measurements of the levels of energy seen at the 2 traditional weakest links of the kinetic chain. We found a near-significant trend toward elbow injury with higher levels of both EV and SER torque throughout the pitching motion. In particular, we found a statistically significantly higher level of both EV and SER torque at the late cocking phase of the pitching cycle in pitchers suffering an elbow injury. These findings confirm long-held theories about elbow injury in pitchers. It has been established that EV torque peaks at the event of maximum external rotation of the shoulder, where values can approach 120 N·m at the professional level.[7,8,22,25] Our study found similar levels of EV torque, and we also saw a peak in these levels at the late cocking phase. Simultaneously, we noted a peak in SER torque values at this point as well, fitting with the kinetic chain theory of how ball velocity is generated.

Pitchers create the energy necessary for high levels of ball velocity with a combination of torso rotation and shoulder internal rotation. Elbow valgus torque has long been theorized as a measure of the deforming torque experienced at the elbow and responsible for the injuries seen in EV extension overload syndrome. Our findings support this theory with documented relation between injury and EV torque at the moment of maximal external rotation. Similarly, shoulder rotational torque is the source of rotational speed at the shoulder. Certain styles of pitching use shoulder rotational speed, as opposed to trunk motion, to produce ball velocity.[1,25] As a result, SER torque is a measure that captures the power at the shoulder and, as such, theoretically measures the potential for injury throughout the kinetic chain. Our findings support the theory that increased magnitudes of this value are a risk factor for elbow injury by documenting a correlation between injury and increased values at the moment of maximal external rotation.

TABLE 5
Comparison of Shoulder External Rotation Torque[a]

Pitch Cycle Event	Injured Group Mean Torque, N·m (SD)	Noninjured Group Mean Torque, N·m (SD)	Least Squared Means *P* Value
SFC	2.62 (7.65)	1.77 (7.29)	.88
MER	89.8 (24.0)	71.0 (24.5)	.0018
REL	6.89 (4.92)	5.26 (6.94)	.78
MIR	−0.36 (4.17)	0.04 (8.06)	.94

[a]At the 4 major points of the pitching cycle, comparison between injured and noninjured groups of mean elbow valgus torque values produced least squared means analysis with *P* values significant only at maximum shoulder external rotation (MER). SFC, stride foot contact; REL, ball release; MIR, maximal internal rotation.

Aguinaldo and Chambers[1] recently showed that EV torque is directly influenced by 6 distinct biomechanical parameters within the kinetic chain. In particular, late trunk rotation, reduced shoulder external rotation, and increased elbow flexion were most closely associated with EV torque levels. Manipulation of these biomechanical parameters could thus possibly affect EV and SER torque levels. Indeed, a recent study by Davis et al[3] showed that youth baseball pitchers with improper mechanics have higher humeral internal rotation torque and higher EV load during pitching. The pitchers with proper mechanics, however, had lower torque values and higher pitching efficiency. Taken in context with our study, these findings imply that implementing proper pitching mechanics can possibly decrease EV and SER torque levels, and thus possibly decrease injury rates. Although studies have shown that pitching mechanics generally improve with level of play,[9,10] the professional-level findings seen in our study have important ramifications at all levels of pitching.

Murray and colleagues[15] analyzed the effects of fatigue on multiple biomechanical parameters of the pitching motion, using a method very similar to our study. They found no significant effect of fatigue on EV or SER torque levels. Another study by Escamilla et al[6] revealed that shoulder and elbow kinetics and kinematics of the pitching motion for a given pitcher do not change over the course of a game as a pitcher fatigues, even though ball velocity may drop off. The findings of these studies further emphasize

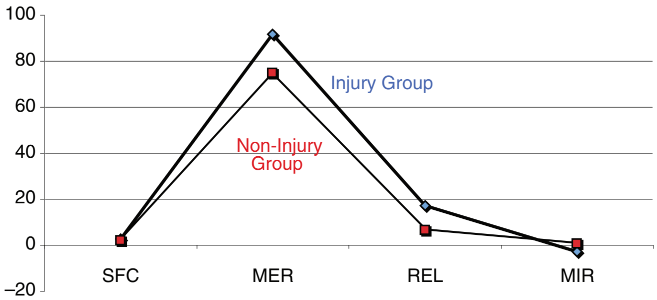

Figure 4. Elbow valgus throughout the pitching motion: stride foot contact (SFC), shoulder maximum external rotation (MER), ball release (REL), and shoulder maximum internal rotation (MIR)

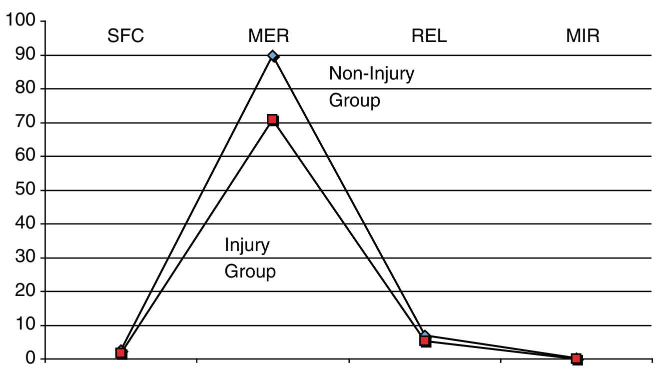

Figure 5. Graph of shoulder external rotation throughout the pitching motion: stride foot contact (SFC), shoulder maximum external rotation (MER), ball release (REL), and shoulder maximum internal rotation (MIR)

the importance of proper mechanics, rather than fatigue, as the primary factor influencing EV and SER torque levels, and thus the ideal primary target of any planned injury-reduction interventions.

One question raised by our findings is the role of ball velocity and pitch type as a risk factor for injury. In a separate study[2] involving the same cohort of pitchers, we indeed found that increasing ball velocity is a distinct independent risk factor for elbow injury and that the 3 pitchers with the highest ball velocities were the 3 who ultimately required ulnar collateral ligament reconstruction. Because our protocol involved analysis of the fastest pitch thrown for a strike (most likely a fastball) and did not directly control for pitch type, we were unable to investigate pitch type as a risk factor for injury. Several studies have investigated the biomechanics of varying pitch types and their influence on injury risk,[5,11,12,16] but our study did not attempt to include pitch type in the data analysis. Our analysis of only 1 pitch is a weakness of our study as it may not correctly quantify the mechanics of the selected pitcher and therefore may not quantify a true risk factor for injury. Future study design involving categorization of a pitcher's style, quantification of EV and SER based on several pitches, and subsequent investigation for injury would be an ideal model design.

In addition to the lack of pitch type analysis, this study did have notable additional weaknesses. The sample size of only 25 pitchers, 2 of whom were unavailable for final analysis, is a source of weakness. Second, the time of videotape data collection may have been an aberration for a given pitcher, resulting in analysis that thus did not truly represent that pitcher's usual pitching motion. Additionally, we restricted observation for injury to 3 subsequent seasons. Although this method opens the possibility of changing pitching mechanics over time as a possible confounder, we thought it was necessary to use more than a single season to capture the overuse effect common to many pitching injuries. Fourth, we did not specifically analyze for shoulder injury as a variable. Shoulder injury could certainly affect elbow injury risk, but we sought to focus only on elbow injury for this study. Indeed, only 3 shoulder injuries were seen in our overall cohort, so we most likely lacked enough power for any meaningful statistical analysis. Finally, a radiologic assessment of our cohort, preferably with magnetic resonance imaging, was not performed before recording biomechanical data; therefore, underlying asymptomatic pathologic abnormalities cannot be ruled out in our cohort. Retrospective analysis of our study's weaknesses allows for better design of future studies to expand on our present results.

CONCLUSION

In conclusion, our study showed that the late cocking phase of the pitching motion is indeed the critical point in terms of elbow injury risk. Additionally, higher levels of EV and SER torque at this event in the cycle are biomechanical risk factors for elbow injury, including injury requiring surgery. This confirms long-held theories concerning the cause of injury in baseball pitchers. As our understanding of pitching mechanics improves, it may be possible to reduce injury risk by focusing on ways to decrease torque levels at this critical point while still maintaining high levels of velocity and overall pitching performance. Additionally, methods of easily calculating these values within the competitive population may help to screen for pitchers at risk for injury.

ACKNOWLEDGMENT

The authors thank Keith Dugger of the Colorado Rockies Training Staff for insight and advice in the preparation of this article.

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