original research

Glenohumeral Rotational Motion and Strength and Baseball Pitching Biomechanics

Wendy J. Hurd, PhD, PT, SCS*; Kenton R. Kaufman, PhD, PE†

*Senior Research Fellow and †W. Hall Wendel Jr Musculoskeletal Research Professor, Mayo Clinic, Rochester, MN

Context: Addressing loss of shoulder range of motion and rotator cuff weakness in injury-prevention programs might be an effective strategy for preventing throwing arm injuries in baseball pitchers. However, the influence of these clinical measures on pitching biomechanics is unclear.

Objective: To evaluate the relationships among clinical measures of shoulder rotational motion and strength and 3-dimensional pitching biomechanics and to evaluate the presence of coupling between the shoulder and the elbow during pitching to provide insight into the influence of clinical shoulder characteristics on elbow biomechanics.

Design: Cross-sectional study.

Setting: Biomechanics laboratory.

Patients or Other Participants: A total of 27 uninjured male high school baseball pitchers (age = 16 ± 1.1 years, height = 183 ± 7 cm, mass = 83 ± 12 kg).

Main Outcome Measure(s): Clinical measures included shoulder internal- and external-rotation range of motion and peak isometric internal- and external-rotator strength. Three-dimensional upper extremity biomechanics were assessed as participants threw from an indoor pitching mound to a target at regulation distance. Linear regressions were used to assess the influence of clinical measures on the peak shoulder internal and external rotation moments and the peak elbow-adduction moment.

Results: We found a positive relationship between clinically measured internal-rotator strength and shoulder external-rotation moment ($R^2 = 0.181$, $P = .04$) during pitching. We also noted an inverse relationship between clinically measured external-rotation motion and the elbow-adduction moment ($R^2 = 0.160$, $P = .04$) and shoulder internal-rotation moment ($R^2 = 0.250$, $P = .008$) during pitching. We found a positive relationship between peak shoulder internal-rotation moment and the peak elbow-adduction moment ($R^2 = 0.815$, $P < .001$) during pitching.

Conclusions: This study provides insight into the effects of shoulder strength and motion on pitching biomechanics and how these clinical measures might contribute to throwing arm injuries in the baseball pitcher. A relationship also was identified between peak shoulder and elbow moments in the throwing arm during pitching, providing biomechanical support for addressing clinical shoulder characteristics as a potential strategy for preventing elbow injury.

Key Words: upper extremity, overhead athletes, throwing athletes, rehabilitation

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Key Points

- A biomechanical coupling existed between peak shoulder internal-rotation moment and peak elbow-adduction moments during pitching.
- Clinically measured internal rotator strength was correlated positively with shoulder external-rotation moment during pitching.
- Clinically measured external-rotation motion was related inversely to elbow-adduction moment and shoulder internal-rotation moment during pitching.

Injuries to the throwing elbow and shoulder are common among youth baseball athletes.[1] Collins and Comstock[2] reported an estimated 131 555 injuries were sustained during the 2005–2006 and 2006–2007 academic years in high school play alone. Ligament sprains and muscle strains are the most common, albeit generic, diagnoses.[2] Common throwing arm injuries in the baseball athlete at the shoulder[3] include rotator cuff tendinitis, superior labrum anterior-posterior lesions, and internal impingement and at the elbow[4] include ulnar collateral ligament (UCL) injury, flexor-pronator tendinitis, and osteochondritis dissecans. Perhaps more alarming than the injuries that these athletes sustain is the frequency with which they play with pain. Lyman et al[5] reported that over the course of a single season, more than 50% of youth pitchers aged 9 to 14 years experienced shoulder or elbow pain. The hypothesized cause underlying upper extremity overuse injuries is cumulative microtrauma associated with

the high-magnitude, repetitive stresses of pitching.[6] Mechanisms contributing to degenerative injuries observed in the adult baseball athlete are believed to be initiated during the athlete's early playing years.[7] Therefore, the best time to prevent injury across all levels of play appears to be at the youth level.[7]

Risk factors for injury have been identified. For the youth player, nonmodifiable factors include advancing age, height, and mass.[8] Modifiable factors include an increasing pitch volume during a game and over the course of a season, throwing breaking pitches (curveballs and sliders), upper extremity fatigue, and inadequate rest over the course of a year.[5,8] Based on these data, USA Baseball[9] provided recommendations for pitch limit and for the age at which an athlete should begin throwing breaking pitches. These efforts, however, have had limited effectiveness in reducing the number of injuries. Cain et al[10] reported on UCL treatment patterns and outcomes

over a 19-year period. The authors stated that the number of reconstructive surgeries, including procedures in adolescent patients, performed at their facility between 1995 and 2006 increased rather than decreased. They suggested the increase in UCL injury and treatment intervention was multifactorial but most likely included a combination of improved diagnostic techniques; heightened awareness; increased change of positive outcome with current operative techniques; and overuse of young throwing arms, which was potentially the most important factor.[10]

Adaptations in shoulder motion and strength might affect a pitcher's risk of injury through alterations in upper extremity biomechanics. Uninjured pitchers exhibit a shift in glenohumeral rotational motion that includes a gain in external-rotation and corresponding loss of internal-rotation motion in the throwing arm.[3,6,11–15] The alterations in shoulder motion manifest during adolescence[13,14,16] and can result from both osseous (humeral head retroversion)[12,17] and soft tissue (posterior shoulder tightness and anterior capsular laxity)[3,6,18,19] adaptations. Although they are normal findings, loss of glenohumeral internal rotation due to posterior shoulder tightness and gain of external-rotation motion associated with increased anterior capsular laxity have been implicated in injuries to the throwing shoulder[3,6,20,21] and elbow.[22]

Bilateral strength differences in the uninjured baseball athlete include less external-rotator strength[23–25] and more internal-rotator strength[26–28] of the throwing shoulder compared with the nonthrowing shoulder. In addition, lower external- to internal-rotator strength ratios have been reported in the throwing shoulder of the asymptomatic baseball athlete.[25,27–30] This alteration in the external-to-internal strength ratio predominantly is due to the presence of greater gains in the internal-rotator strength of the dominant arm without an equivalent increase in the strength of the external rotators.[27,31] Marked muscle activity of the external rotators has been reported during the late stage of cocking[32] and has been suggested to restrain the humeral head within the glenoid fossa during this phase of pitching.[33] A decrease in force generation of the external-rotator muscles or a low external-to-internal rotator strength ratio, therefore, has the potential to lead to faulty humeral head positioning by permitting excessive anterior humeral head migration, negatively affecting biomechanics of the pitching arm. It is not surprising, then, that external-rotator muscle weakness or a marked decrease in the external-to-internal rotator strength ratio has been associated with shoulder lesions, including internal impingement, anterior shoulder instability, labral lesions, and rotator cuff lesions, particularly in the overhead athlete.[21,34–38]

The shoulder potentially can affect the development of elbow injury in the baseball athlete. Dines et al[22] compared range-of-motion characteristics of the shoulder and elbow in 29 baseball players with UCL insufficiency with 29 demographically matched baseball players with no history of shoulder or elbow injury. They[22] reported a difference between groups for shoulder internal-rotation motion of the dominant arm, with the injured group demonstrating less motion (mean = 29°) than the control group (mean = 38°). Based on these findings, the authors[22] advocated restoration of shoulder flexibility

when treating athletes with UCL injury. Therefore, evaluating the presence of biomechanical coupling during pitching might provide insight into how the shoulder might affect the development of elbow injury in the baseball athlete.

Shoulder mobility and strength represent modifiable characteristics in the baseball athlete. Consequently, addressing loss of motion and muscle weakness in injury-prevention programs might be an effective strategy for preventing injuries to the throwing extremity in this population. However, we are unaware of previous studies in which researchers have evaluated the relationships between clinical characteristics and upper extremity biomechanics in these athletes. Therefore, the purpose of our study was to evaluate the relationships between clinical measures of shoulder rotational motion and strength and 3-dimensional (3D) pitching biomechanics in uninjured baseball pitchers. Biomechanical variables of interest for the pitching arm included internal moments at the shoulder and elbow. A *joint moment* is the product of a force and the perpendicular distance from its line of action to that point and tends to rotate the object about its axis. An internal joint moment consequently might be considered representative of the stresses placed on tissues to overcome external forces. Specific variables were selected based on their potential insight into injury. The *peak elbow-adduction moment* represents the stress to the medial aspect of the elbow to counter valgus opening, which might contribute to the risk of UCL injury. The *peak shoulder internal-rotation moment* represents the stress to counter external-rotation motion and was chosen to represent stress to the anterior aspect of the glenohumeral joint, which might contribute to functional instability of the anterior aspect of the shoulder. Finally, the *peak shoulder external-rotation moment* represents the stress to counter internal-rotation motion and was selected to represent stress to the posterior aspect of the shoulder, potentially contributing to increased activity of the posterior rotator cuff musculature (external rotators). A secondary purpose of our study was to evaluate the presence of coupling between the shoulder and elbow during pitching to provide insight into the influence of clinical shoulder characteristics on elbow biomechanics.

METHODS

Participants

A random sample of 27 uninjured male high school-aged baseball pitchers (age = 16 ± 1.1 [range, 15 to 19] years, height = 183 ± 7 cm, mass = 83 ± 12 kg) was recruited for the study. All participants had a minimum of 3 years of experience (6 ± 2.3 years) competing in organized baseball as a starting pitcher. Five participants were left-arm dominant and 22 were right-arm dominant pitchers. The absence of injury to either upper extremity was confirmed by a clinical screening performed by a sports-certified physical therapist (W.J.H.). The manual examination included assessment of both the shoulder and elbow for joint injury with specific tests for rotator cuff tendinitis or impingement, labral tearing, posterior impingement, UCL injury, valgus-extension overload, flexor-pronator tendinitis, and neurologic involvement. Finally, athletes were

required to have a QuickDASH[39] sports score of equal to or less than 10% to participate in the study, with lower scores associated with higher levels of function. A history of upper extremity injury did not preclude participation in the study if the athlete had made a full return to participation in baseball activities. Parents provided written informed consent, and participants provided assent. The study was approved by the Mayo Clinic Institutional Review Board.

Clinical Measures

Passive shoulder internal and external range of motion was measured in the pitching arm with the humerus abducted to 90° while the participant lay supine. Measurements were performed with a standard long-armed clinical goniometer with a bubble level secured to the reference arm to facilitate proper alignment.[14,40] The axis of the goniometer was positioned over the olecranon, the moving arm was parallel to the midline of the forearm and in alignment with the ulnar styloid process, and the reference arm was perpendicular to the floor.[41] A rolled towel was placed under the humerus to position the arm in alignment with the trunk. Joint stabilization was provided by the table and with the examiner placing 1 hand on the anterior aspect of the glenohumeral joint.[40] Testing consisted of moving the participant's extremity through a full arc of motion until an end point was reached. *End of motion* was defined as a cessation of motion or the point at which scapular protraction was appreciated.[40] A single examiner (W.J.H.) performed all range-of-motion testing, and an assistant (not an author) aligned the goniometer and recorded the measurement. Two trials were performed for each motion measured, and the average was used for analysis. Repeatability of goniometric measures was established in a sample of uninjured participants and was excellent, with intraclass correlation coefficient (ICC) values ranging from 0.944 to 0.990 for the motions of interest. Within-study repeatability testing yielded trial-to-trial variability of less than 5°.

Maximal voluntary isometric strength of the shoulder internal and external rotators of the throwing arm was measured with a handheld dynamometer (Commander PowerTrack II; JTECH Medical, Salt Lake City, UT) using a break test (Figure 1). During testing, participants were seated on a table without trunk support, the hips and knees were flexed to 90°, and the upper extremity was abducted to 90°. Compensations by participants to enhance force production were minimized with oral cuing, positioning, and having an assistant (not an author) manually stabilize the arm in the abducted position.[42] Additionally, participants were permitted to grasp the table with the upper extremity not being tested to minimize trunk movement.[42] For the test, the dynamometer was positioned just proximal to the dorsal surface of the wrist for external rotation and the volar surface for internal rotation. Participants performed 1 submaximal practice trial for each measure of interest to become acclimated to the testing procedures. Next, two 5-second test trials were performed for both the internal and external rotators. The peak force production from each trial was recorded, and the average of the 2 trials was used for analysis. Repeatability of strength values was established in a sample of uninjured participants and was excellent, with ICC values ranging from 0.934 to 0.977 for the variables of interest. Within-study repeatability testing yielded trial-to-trial variability of less than 2.6 kg. This translated to less than 3% of peak torque/body mass measurement variability for the sample.

Motion Analysis Testing

Kinematic data were collected with a 10-camera, 3D motion-capture system (Motion Analysis Corporation, Santa Rosa, CA). Retroreflective markers were secured over anatomic landmarks and used to define joint centers and joint axes, measure segment length, and track motion (Figure 2). Motion data were collected at 500 Hz and low-pass filtered at 6 Hz with a fourth-order, zero-lag digital Butterworth filter.
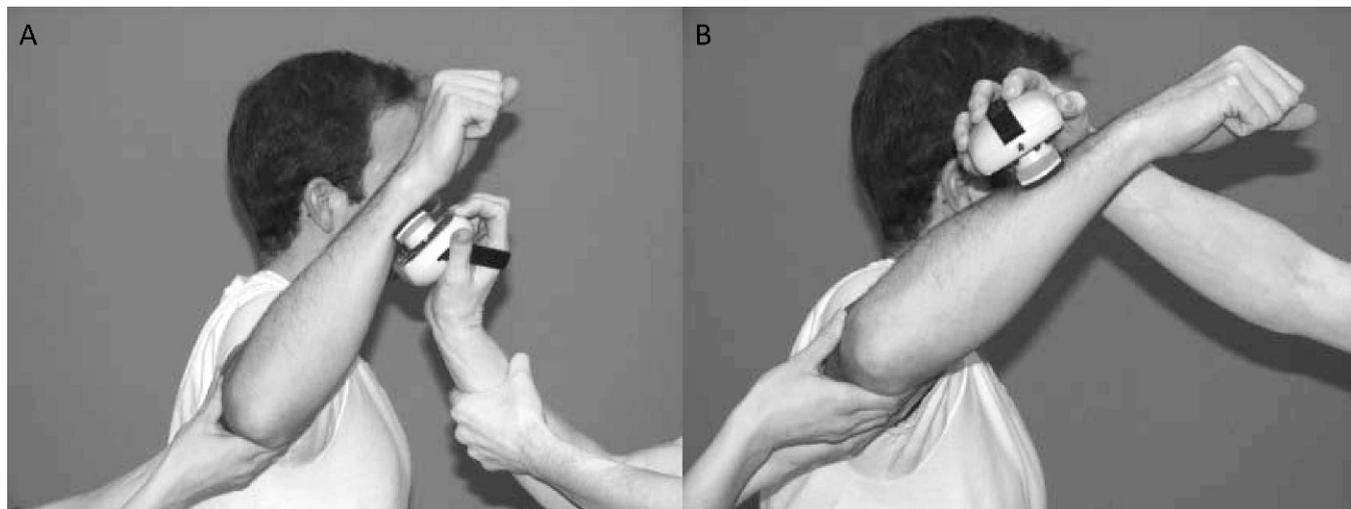

Figure 1. Participant positioning. A, Internal rotation strength testing. B, External rotation strength testing. Reprinted with permission from Hurd WJ, Kaplan KM, ElAttrache NS, Jobe FW, Morrey BF, Kaufman KR. A profile of glenohumeral internal and external rotation motion in the uninjured high school baseball pitcher, part II: strength. *J Athl Train.* 2011;46(3):289–295.
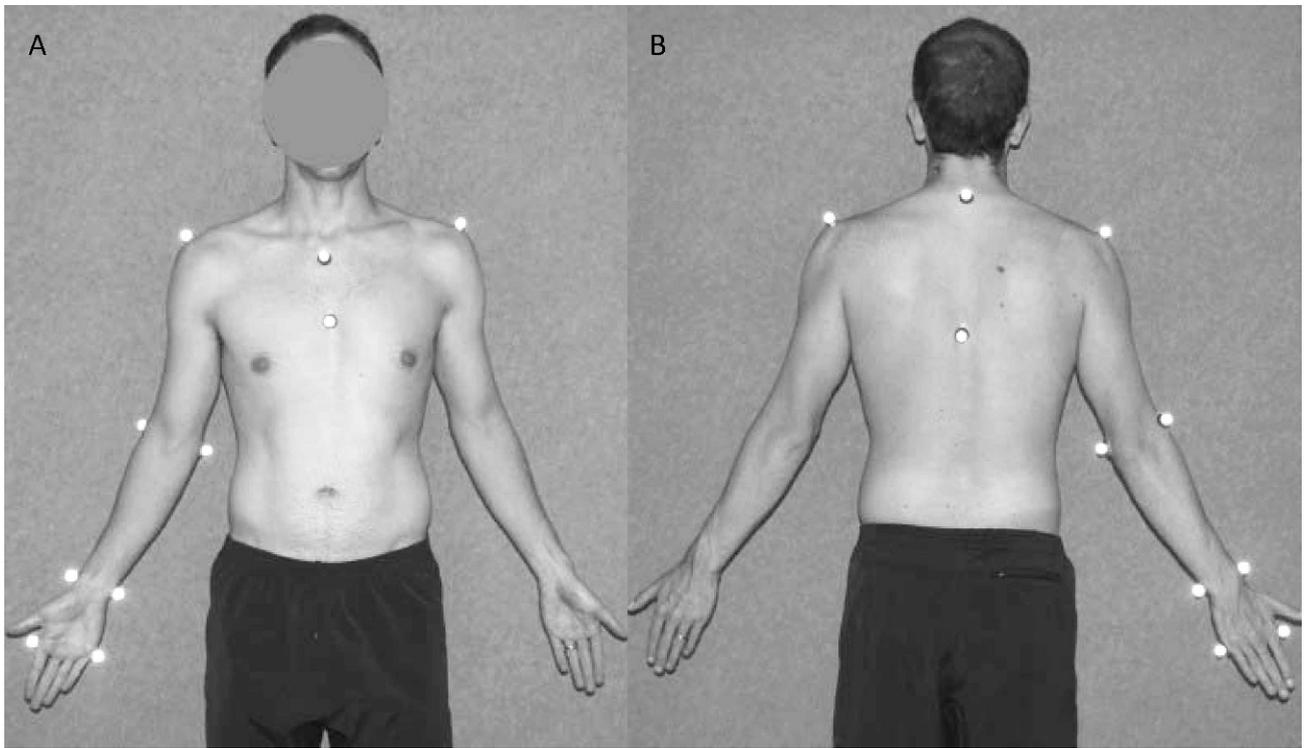
Figure 2. Marker placement. A, Anterior view. B, posterior view.

Participants were positioned in an anatomic neutral position in the camera's field of view, and a reference trial was captured. Next, participants completed a 15-minute individualized warm-up consisting of stretching, jogging, and light tossing to prepare for testing. Test trials consisted of 10 fastballs thrown for strikes from a full windup (pitches thrown = 17 ± 4). Athletes threw from an indoor pitching mound to a target at regulation distance (18.4 m). The target consisted of a net on which a simulated strike zone (46×22 cm) was outlined. All participants wore gloves on their nonpitching hands and indoor turf shoes (ie, none wore cleats). An assistant (not an author) positioned behind the target recorded pitch velocity with a radar gun (JUGS Sports, Tualatin, OR). Only pitches within 5% of the mean and thrown for a strike were included in the analysis.

Data Management and Analysis

Kinematic and kinetic variables were calculated using Visual3D (C-Motion Inc, Germantown, MD) based on a 3D, 6-degrees-of-freedom model of the upper extremity that has been described in detail.[43] The model consisted of rigid body segments, including the trunk, arm, forearm, and hand. The magnitude of kinematic errors using this model in our laboratory was less than 3°. Euler angles were used to describe elbow and shoulder kinematics, with the exception of transverse-plane shoulder kinematics. Preliminary analysis indicated helical angles yielded the most appropriate description of shoulder internal and external rotation with the extremity abducted to 90°. Joint kinetics were derived using inverse dynamics.[44] The inertial properties[45] of the hand, forearm, and arm were calculated using the force of the baseball, which was modeled as a 142-g mass with the point of force application on the hand assumed to be between the second and fifth metacarpal heads.

Clinical variables of interest included passive internal- and external-rotation motion of the pitching arm and peak isometric external and internal rotator strength. Strength values were normalized to participant mass to permit between-subjects comparisons. Biomechanical variables of interest included peak elbow-adduction moment, peak shoulder internal-rotation moment, and peak shoulder external-rotation moment. Moments were expressed internally and normalized to the mass and height of the participant. Statistical testing consisted of linear regression analysis to determine the influence of clinical variables of interest on pitching biomechanics. Linear regression analysis also was performed to evaluate the influence of the peak shoulder internal-rotation moment on the peak elbow-adduction moment to assess the coupling of moments between these joints. The α level was set at .05. We used IBM SPSS Statistics (version 19.0; IBM Corporation, Armonk, NY) to analyze the statistics.

RESULTS

Clinical measures of shoulder range of motion included mean external rotation of $127° \pm 10°$ and internal rotation of $59° \pm 9°$ (Table 1). Clinically measured mean shoulder external-rotator strength was $17\% \pm 3\%$ of body mass and internal-rotator strength was $25\% \pm 6\%$ of body mass. Group means for biomechanical variables of interest included a peak elbow-adduction moment of 0.57 ± 0.09 Nm · height^{-1} · mass, peak shoulder internal-rotation moment of 0.61 ± 0.08 Nm · height^{-1} · mass, and peak external-rotation moment of 0.08 ± 0.04 Nm · height^{-1} · mass.

External-rotation motion was a predictor of both the peak elbow-adduction moment and the peak shoulder internal-rotation moment because greater motion was

Table 1. Group Results for Clinical and Biomechanical Variables of Interest

Variable	Mean ± SD
Clinical measures	
External-rotation motion, °	127 ± 10
Internal-rotation motion, °	59 ± 9
Total rotational motion, °	185 ± 14
External-rotator strength, %[a]	17 ± 3
Internal-rotator strength, %[a]	25 ± 6
External-to-internal rotator strength ratio, %	72 ± 14
Biomechanical measures	
Peak elbow-adduction moment, Nm · height^{-1} · mass	0.57 ± 0.09
Peak shoulder internal-rotation moment, Nm^{-1} · height · mass	0.61 ± 0.08
Peak shoulder external-rotation moment, Nm^{-1} · height · mass	0.08 ± 0.04

[a] Indicates normalized to body mass of participants.

associated with smaller moments (Figures 3 and 4; Table 2). We found no relationship between external-rotation motion and the peak shoulder external-rotation moment. We also noted no relationship between internal-rotation motion and any of the biomechanical variables of interest (Table 2).

Shoulder internal-rotator strength was a predictor of the peak shoulder external-rotation moment, as greater strength was associated with larger moments (Figure 5; Table 2). We found no other relationships between clinical strength measures and the biomechanical variables of interest (Table 2).

Finally, the peak shoulder internal-rotation moment was a predictor of the peak elbow-adduction moment. A positive relationship existed between these moments ($R^2 = 0.815$, $P < .001$; Figure 6).

DISCUSSION

Our results provide insight into the effect of shoulder range of motion and strength on pitching biomechanics because greater internal-rotator strength and less external-rotation motion were associated with increases in shoulder and elbow moments. A relationship also was identified between the peak shoulder and elbow moments in the throwing arm during pitching. This finding provides biomechanical support for addressing clinical shoulder characteristics as a potential strategy for prevention and rehabilitation of elbow injuries.

Internal-rotator strength was associated positively with the peak shoulder external-rotation moment, with this strength measure accounting for 18% of the variability in the moment. This would suggest that as strength of the internal rotators increases, demand on the posterior musculature during pitching also increases to counter limb acceleration. The internal rotators are the primary upper limb accelerators during pitching.[32,33,46,47] Consequently, unilateral muscle hypertrophy and strength gains within this muscle group are a common finding in the thrower.[26–28] Advancements in strength potentially can produce greater limb acceleration.[48] Thus, the greater shoulder external-rotation moment partly represents the eccentric demand on the posterior portion of the rotator cuff that is necessary to counter the rapid internal-rotation motion of
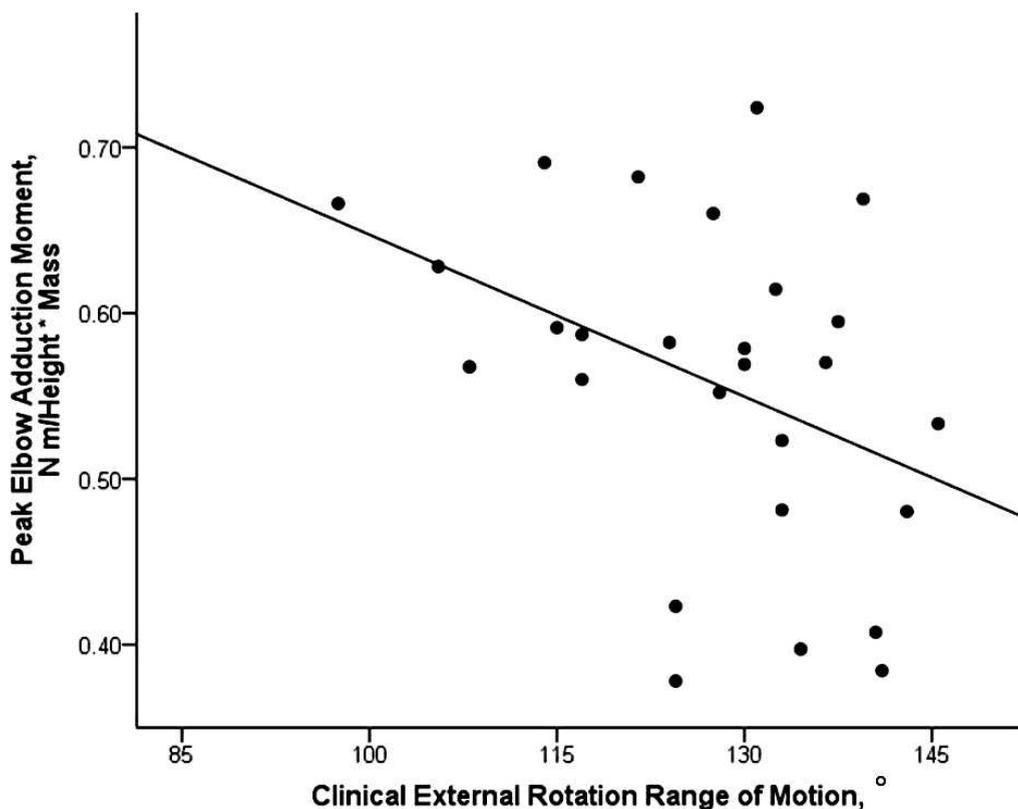

Figure 3. Linear regression analysis between shoulder external-rotation range of motion and the peak elbow-adduction moment ($R^2 = 0.160$, $P = .04$).
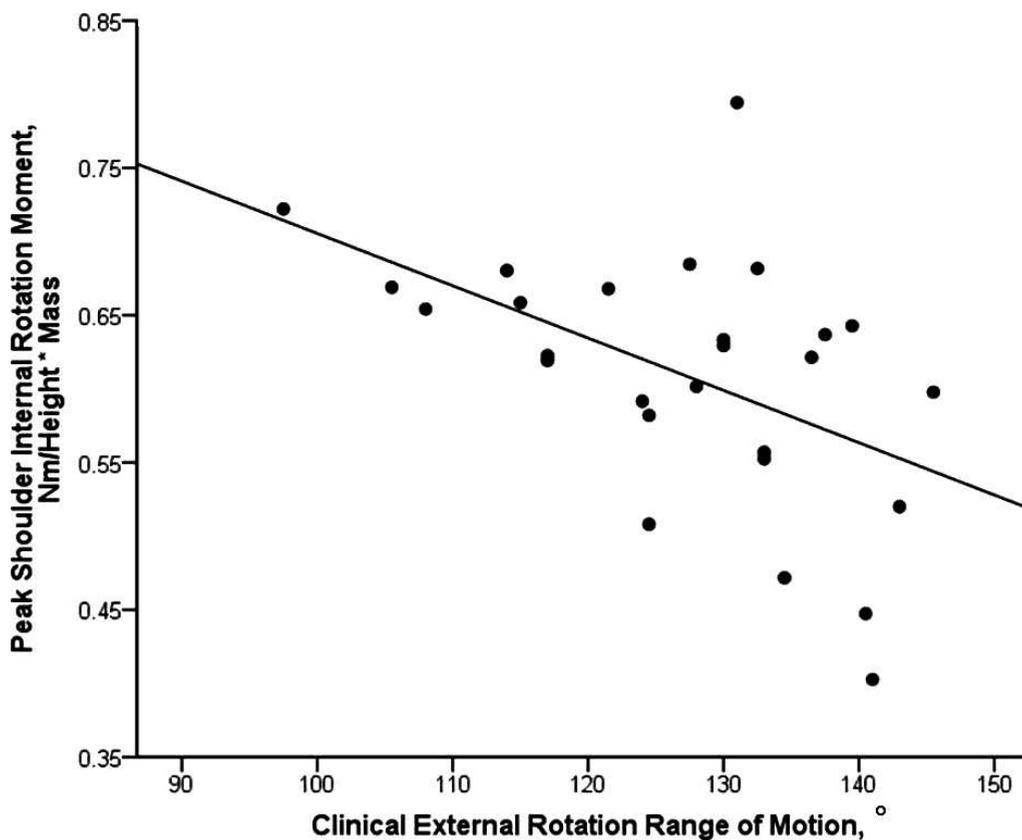
Figure 4. Linear regression analysis between shoulder external-rotation range of motion and the peak shoulder internal-rotation moment ($R^2 = 0.250$, $P = .08$).

the upper extremity. This demand on the musculature of the posterior aspect of the shoulder suggested by the external rotation moment is consistent with findings reported in previous electromyography (EMG) studies in which investigators documented rotator cuff muscle activity during pitching.[32,33,46,47] However, the peak external-rotation moment that we measured was low compared with the internal-rotation and the elbow-adduction moments. Therefore, we question whether the

Table 2. Linear Regression Results

Variable	R^2	P Value
External-rotation range of motion		
Peak elbow-adduction moment	0.160	.04[a]
Peak shoulder internal-rotation moment	0.250	.008[a]
Peak shoulder external-rotation moment	0.002	.82
Internal-rotation range of motion		
Peak elbow-adduction moment	<0.001	.97
Peak shoulder internal-rotation moment	<0.001	>.99
Peak shoulder external-rotation moment	0.118	.11
External-rotator strength		
Peak elbow-adduction moment	0.001	.87
Peak shoulder internal-rotation moment	0.004	.75
Peak shoulder external-rotation moment	0.019	.54
Internal-rotator strength		
Peak elbow-adduction moment	0.021	.47
Peak shoulder internal-rotation moment	0.033	.36
Peak shoulder external-rotation moment	0.181	.04[a]

[a] Indicates difference ($P < .05$).

greater moments associated with internal-rotator strength represent a meaningful increase in risk of injury.

Reports regarding the clinical effect of internal rotator strength in the baseball athlete are contradictory. Byram et al[49] evaluated preseason shoulder strength over 5 seasons in professional baseball pitchers. Players were followed prospectively throughout the season for incidence of throwing-related injuries. The authors[49] reported no association between isometric internal-rotator strength and the likelihood of shoulder injury. These findings conflict with those of Harada et al,[50] who assessed risk factors for elbow injury in 294 youth baseball players aged 9 to 12 years. The risk factors for injury that they evaluated included clinical measures of motion and strength, age, height, mass, grip strength, grip-strength ratio, position, years of throwing experience, number of pitches thrown, and number of days and hours of training per week. Sixty participants had injuries. Ultrasonography was used to confirm the pathologic lesions in 50 of the participants who agreed to undergo additional testing. Diagnoses were medial epicondylar fragmentation in 48 participants and osteochondritis dissecans of the capitellum in 2 participants. The authors[50] reported athletes were at risk for elbow injury (odds ratio = 2.04) if their internal-rotator strength exceeded 100 N. Harada et al[50] hypothesized the greater strength could contribute to elbow injury by increasing upper extremity velocity and thus increasing distraction forces in the medial aspect of the elbow. Our data did not support this hypothesis, given that we found no relationship between internal-rotator strength and the elbow-adduction moment. Because Harada et al[50] did not normalize the strength to participant height or mass, between-studies
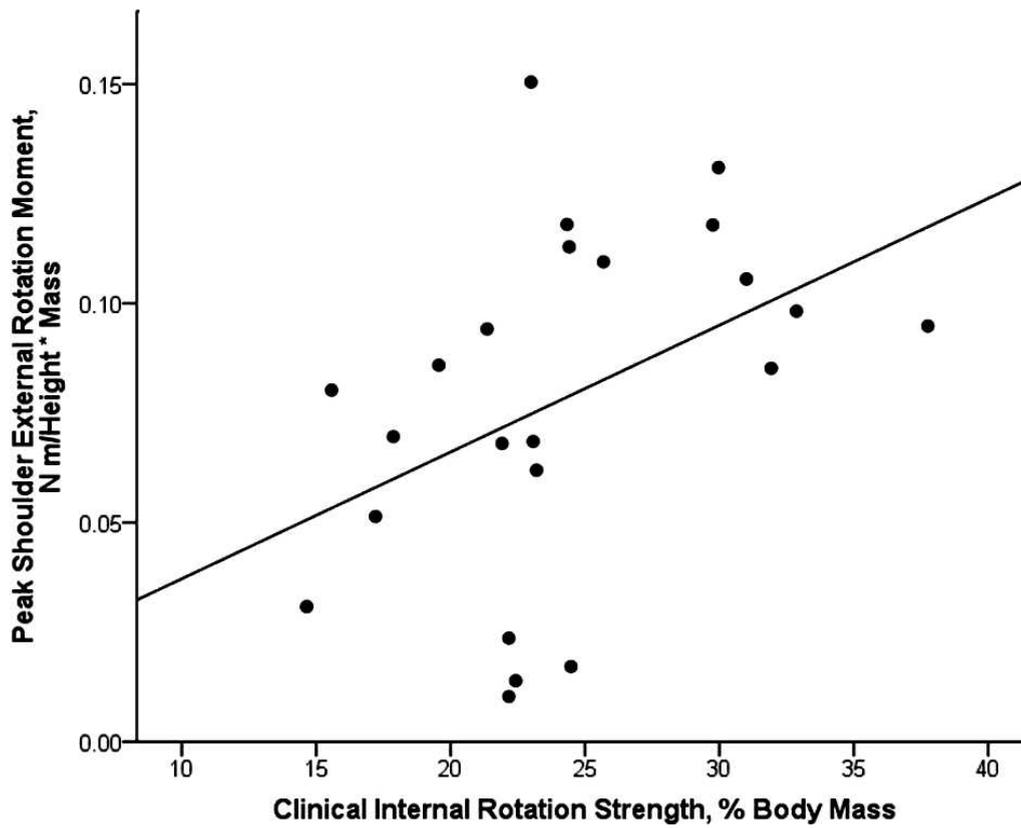
Figure 5. Linear regression analysis between shoulder internal-rotator strength and the peak shoulder external-rotation moment ($R^2 = 0.181$, $P = .04$).
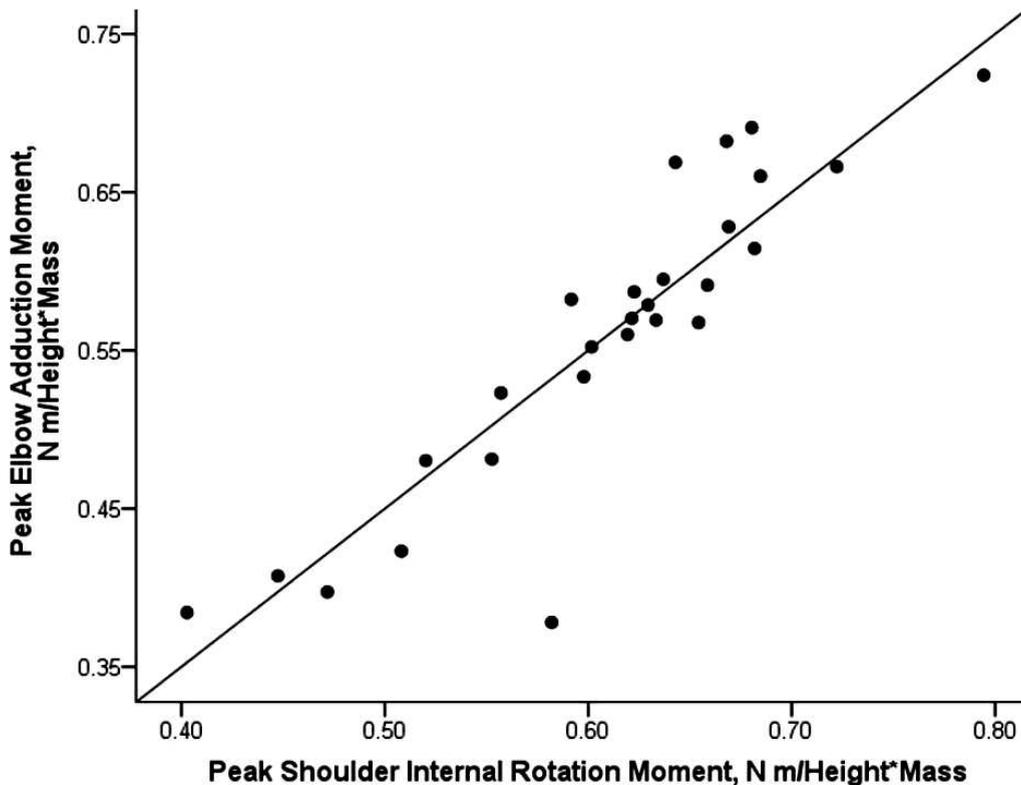

Figure 6. Linear regression analysis between the peak shoulder internal-rotation moment and the peak elbow-adduction moment ($R^2 = 0.815$, $P < .001$).

comparisons are difficult. The older participants, who were larger and able to produce greater muscle force, possibly sustained elbow injuries due to their throwing volumes.

Greater clinical measures of external-rotation motion were associated with lower peak elbow-adduction moments and lower peak shoulder internal-rotation moments. Clinically measured external-rotation motion accounted for 16% of the variability in the elbow moment and 25% percent of the variability in the shoulder moment. This suggests that greater external-rotation motion might protect the medial aspect of the elbow from injuries, potentially decreasing the stress on the anterior aspect of the shoulder and minimizing the risk of anterior glenohumeral instability. This biomechanical relationship is in agreement with the findings of Harada et al,[50] who reported that clinical measures of passive shoulder external-rotation motion less than 130° were a risk factor for elbow injury in youth baseball athletes (odds ratio = 1.98). However, shoulder external-rotation motion measured during pitching has been associated with larger moments of the medial aspect of the elbow. Aguinaldo et al[51] evaluated 3D biomechanical analysis of the pitching motion in 69 uninjured adult baseball players. The authors reported maximum shoulder external rotation during the pitching motion was correlated positively with the peak elbow-valgus torque, with greater motion equating to higher torque.[51] Sabick et al[52] reported similar findings in 14 uninjured youth pitchers; maximum shoulder external rotation during the pitching motion was the best biomechanical predictor of peak elbow-valgus torque. They stated that the pitchers who externally rotated their arms the most during pitching stressed their elbows more severely and were consequently at greater risk of elbow injury.[52]

We suggest that the increase in shoulder mobility as captured by clinically measured external rotation might result in lower joint stresses during pitching. For example, the athlete who has less available external rotation and takes his shoulder to the end of the available joint motion during pitching might place an increased demand on the soft tissue structures of the shoulder and elbow. In the athlete with greater external-rotation motion, the peak motion during pitching might not be extended to the limits of the available joint motion. This would result in lower demands on passive joint stabilizers while increasing the demands on the dynamic muscular stabilizers to control joint motion. The ultimate effect of clinically assessed motion on injury risk must be determined with future investigations that incorporate a prospective, longitudinal study design.

We found a strong relationship between the peak shoulder internal-rotation moment and the peak elbow-adduction moment measured during pitching, with 81% of the variability in the elbow moment accounted for by the shoulder moment. The direct relationship between pitching biomechanics of the shoulder and elbow injury was described by Anz et al,[53] who performed 3D motion analysis of the pitching motion in 23 uninjured professional pitchers. The pitchers subsequently were followed for the next 3 seasons for injuries. The authors reported a correlation between elbow injury and higher values of shoulder external-rotation torque, which is a kinetic variable equivalent to the shoulder internal-rotation

moment that we evaluated.[53] Unfortunately, they did not normalize kinetic values to the height or body mass of their participants, limiting the ability to compare values across studies.[53]

We believe the coupling between these shoulder and elbow moments during pitching is partly due to limb positioning and geometry as the extremity is accelerating forward during the pitching motion. The same external forces contributing to an adduction moment at the elbow simultaneously are producing an internal-rotation moment at the shoulder. Consequently, throwing athletes might be equally vulnerable to injury to both the shoulder and elbow.[54] This might provide insight into why athletes who return to play after injury at one site subsequently injure the adjacent upper extremity joint.

Our investigation had limitations. We possibly did not identify a relationship between clinical measures of external-rotator strength and internal-rotation motion and pitching biomechanics due to our strength-testing methods. During pitching, the critical role of the posterior portion of the rotator cuff is to act eccentrically and decelerate the humerus. Because we were interested in assessing maximum muscle force, strength was tested isometrically. A relationship between shoulder external-rotator strength and the internal-rotation moment might have been identified if strength had been assessed eccentrically, replicating the manner in which the musculature functions during pitching. Another potential methodologic limitation was the inability to precisely measure the small-magnitude glenohumeral translations during pitching with existing motion-capture systems. Although more sensitive motion-assessment techniques, such as biplane radiography, are available to measure joint arthrokinematics, tracking joint motion during pitching is not possible secondary to the dynamic nature of pitching and the large collection volume necessary to capture the entire pitching motion. In addition, we inferred joint moments as representative of demands on musculature around the glenohumeral joint. Complementary EMG data might have provided greater insight into muscle activity during pitching. Multiple musculoskeletal adaptations might occur in the unilateral overhead athlete. We evaluated a limited number of clinical characteristics that might influence pitching biomechanics. The effect of additional measures, such as scapulothoracic strength, proprioception, and cervicothoracic motion, on pitching biomechanics also merits investigation. Finally, we incorporated a cross-sectional study design with a population of uninjured, asymptomatic baseball pitchers. Future studies incorporating a prospective, longitudinal design might be necessary to gain further insight into the relationship between these clinical and biomechanical variables and to determine the threshold at which clinical measures increase an individual's risk of injury.

CONCLUSIONS

We identified a relationship between clinical measures of shoulder external-rotation motion and internal-rotator strength and upper extremity pitching biomechanics. A biomechanical coupling also was identified between peak shoulder and elbow moments during pitching. These results provide insight into clinical factors that might be contributing to throwing-related injury in the baseball pitcher.

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Address correspondence to Wendy J. Hurd, PhD, PT, SCS, Charlton North Building, L110, Mayo Clinic, Rochester, MN 19716. Address e-mail to hurd.wendy@mayo.edu.