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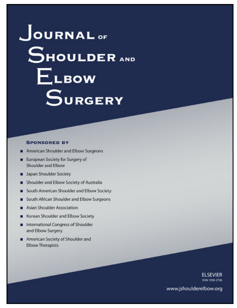

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Short title: Predictors of elbow stress in college pitchers

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Abstract

Hypothesis: College pitchers with increased external rotation gain (ERG) produce increased medial elbow torque (elbow stress), while those with reduced total rotational range of motion (TROM) have reduced medial elbow torque, during pitching.

Methods: Pitchers were recruited from three college baseball teams. Players with prior injury or on pitching restrictions due to pain were excluded. Players were evaluated within two weeks before their first game of the season. Pitchers completed an intake survey and shoulder and arm measurements were taken. Pitchers were fitted with a baseball sleeve which included a sensor at the medial elbow. The sensor calculated elbow torque, arm speed, arm slot, and shoulder rotation for each pitch, while a radar gun measured peak ball velocity. After adequate warmup, pitchers threw 5 fastballs in a standardized manner off the mound at game-speed effort. The primary outcome was to evaluate the relationship between shoulder range of motion (ROM) and medial elbow torque. Additional outcomes evaluated pitcher characteristics and demographics in the context of shoulder ROM.

Results: Twenty-eight pitchers were included in the preseason analysis. The average [standard deviation] age and playing experience was 20.1 [1.3] years and 15.3 [1.8] years, with 2.5 [1.2] years playing at collegiate level. The dominant shoulder demonstrated decreased internal rotation (IR) and increased external rotation (ER) relative to the non-dominant side ($p < 0.001$). The average glenohumeral internal rotation deficit (GIRD) and ERG were 11.3° [9.87] and 5.71° [8.8] degrees, respectively. ERG>5° was found to be a significant predictor of elbow stress during pitching (47.4 [0.7] vs 45.1 [0.6] Nm, P=.014). Univariate associations demonstrated each additional degree of ER resulted in increased elbow torque (beta estimate = 0.35Nm +/- 0.06, P=.003). Conversely, decreased medial elbow torque was found in pitchers with reduced shoulder ROM (GIRD>20°: 43.5 [1.1] vs 46.6 [0.5] Nm, P=.011; loss of TROM>5°: 43.6 [1.1] vs 46.6 [0.5] Nm, P=.013), and in those with greater arm length (P<.05).

Conclusions: College pitchers with increased external rotation produce greater medial elbow torque during the pitching movement. Each degree of increased external rotation was found to corelate with increased elbow torque and ball velocity. On the contrary, arm length and reduced shoulder range of motion were associated with reduced medial elbow torque. This study suggests that increased external rotation in pitchers is associated with greater elbow stress during pitching.

Level of Evidence: Basic Science Study; Kinesiology

Keywords: UCL, Ulnar Collateral Ligament, Pitching, Tommy John, GIRD, Glenohumeral Internal Rotation Deficit, Elbow, Injury

Overhead athletes, particularly baseball pitchers, are at risk of upper extremity injury throughout their careers.[15] Of these, elbow injuries are responsible for the greatest number of days missed and pitchers are the most likely to require surgery**.**[8] Side-to-side variations in shoulder range of motion (ROM) between the dominant throwing arm and the nondominant arm have been identified in baseball pitchers. These variations have been defined as glenohumeral internal rotation deficit (GIRD), external rotation gain (ERG), and loss of total range of motion

(TROM).[27] It has been proposed that GIRD > 20°, ERG > 5° and loss of TROM > 5° represent pathological shoulder ROM adaptations,[14,27] which may predict an increased risk of elbow injury.[27]

The biomechanics of pitching has been well studied, linking aberrations in shoulder motion to pain and symptoms at the elbow likely due to energy transfer in the kinetic chain during the throwing motion.[1] Specifically, several studies have demonstrated that the maximal opening stress at the medial elbow occurs during the late cocking and early acceleration phase of pitching, at which point the shoulder is at its maximal point of external rotation.[10,12,13] The increased volume and repetitive nature of overhead throwing in baseball pitchers eventually leads to downstream adaptive changes,[6] such as increased UCL thickness and elbow laxity.[2,3,7,11,16,21,22] These adaptations may indicate increased risk of elbow injury,[11] while resolution of these adaptations appear contingent on concomitant adaptations in shoulder ROM.[17] Furthermore, shoulder ROM adaptations such as GIRD and ERG have been linked to the development of elbow pathology.[14,15]

Recently, several studies have attempted to identify predictors of increased medial elbow torque (elbow stress) using wearable sensor technology, under the premise that increased stress at the medial elbow drives the degenerative changes leading to elbow injury.[5,19,20,23,25,26,29] In youth, high school, and professional pitchers, fastballs and ball velocity have been implicated as predictors of medial elbow torque.[19,23,29] In high school pitchers, GIRD was interestingly determined to be protective against medial elbow torque; however, this cohort's averaged age was 15.4 [1.03] years old and may not be generalizable to physically mature adults.[29] Despite the understanding of normal shoulder biomechanics during the pitching motion, it remains unclear how adult pitchers' adaptive shoulder ROM (i.e. GIRD and ERG) is associated with stress at the medial elbow.

The purpose of this study was to investigate the relationship between glenohumeral internal rotation deficit (GIRD), external rotation gain (ERG), and loss of total rotational range of motion (TROM) of the shoulder, to torque across the medial elbow during throwing in collegiate pitchers. Secondary outcomes included the influence of pitcher demographics and arm dimensions on pitching measurements. We hypothesized that increased external rotation would contribute to increased medial elbow torque, while decreased shoulder rotation would result in reduced medial elbow torque, in college pitchers.

Methods

This is a prospective observational study of shoulder range of motion deficits as predictors of medial elbow torque during throwing in Division II NCAA college pitchers. Institutional board review was granted for this study (no. 12481). Each participant gave informed consent prior to data collection. The wearable sensor technology and vendor were not involved in funding or design of this study. Pitchers from three Division II NCAA universities were eligible for consideration to the study. Players older than 18 who described their primary position as pitcher were included. Exclusion criteria included upper extremity pain or injury, restricted activity or pitching, a history of surgery on the dominant extremity, and nontraditional pitching styles, predominately pitching side arm or "submarine" style. Of the 41 pitchers who were recruited, 11 pitchers declined to participate during the recruitment phase. Of the 30 pitchers who elected to participate, 2 were excluded from the study due to upper extremity pain and pitching restrictions imposed by the coaching staff.

All pitchers completed a standard intake form that recorded age, hand dominance, injury history, and workload history prior to college. Player data such as height, weight, body mass index (BMI), total arm length, upper arm length, forearm length, and elbow circumference were collected at team practice sessions within the two weeks prior to the first game of the season. The total arm length was considered the distance from the lateral aspect of the acromion to the distal aspect of the fifth digit. Upper arm length was from the acromion to the lateral epicondyle of the humerus. Forearm length was measured from the lateral epicondyle of the humerus to the radial styloid. Elbow circumference was measured around the medial and lateral epicondyles of the humerus. Anthropometric and arm length measurements in this study were consistent with previous studies implementing a wearable sensor device.[23]

Shoulder ROM was recorded prior to any throwing at the practice sessions. ROM measurements included both dominant and nondominant shoulder abduction, forward flexion, neutral external rotation, and supine internal and external rotation in abduction. Shoulder forward flexion and abduction was recorded by having the subject standing upright, with one examiner behind the subject stabilizing the scapula and instructing the subject to elevate the arm to end range of motion, at which point a second examiner employed a goniometer to record ROM in degrees. For supine internal and external rotation in abduction, participants were instructed to lay supine on an examination table. The shoulder was then positioned to 90° abduction and elbow flexion with the forearm perpendicular to the floor in neutral position. To stabilize the scapula, posterior pressure was applied at the acromion. The subject then internally or externally rotated their arm to end ranges of motion, while a second examiner employed a goniometer to record internal and external ROM (Figure 1). Range of motion of both upper extremities were measured in standardized fashion by the same two investigators for every study subject.

Shoulder ROM was further categorized in terms of GIRD, ERG, and loss of TROM, which calculated between dominant and non-dominant shoulders consistent with the literature.[27] GIRD was defined as the internal rotation (IR) of the dominant shoulder subtracted from the non-dominant shoulder. ERG was defined as the external rotation (ER) of the non-dominant shoulder subtracted from the dominant shoulder. Loss of TROM was defined as the sum of the ER and IR of the dominant shoulder subtracted from the sum of the ER and IR of the non-dominant shoulder. For the purposes of statistical analysis, shoulder ROM was analyzed as a continuous variable, while pitchers with GIRD > 20°, ERG > 5°, and loss of TROM > 5° were compared to those without in a separate analysis.

Pitching data was collected during the participant's practice using a wearable sensor sleeve. This device is an arm sleeve containing a medial elbow pocket that houses a sensor securely inside the throwing sleeve and outputs accelerometer and gyroscope data to be recorded by a mobile phone application (motusTHROW v 8.3.3; Motus Global). The wearable device records elbow torque (Newton meters, Nm), arm slot (degrees, deg), arm speed (rotations per minute, RPM), and shoulder rotation (deg). The device was consistently placed so that the sensor rested 1.5 inches distal to the medial epicondyle of the humerus, as directed by the device manufacturer's instructions (Figure 2). As a motion sensing device, it has been validated against the gold standard of motion capture video analysis for its capacity to measure arm motion and elbow stress during the pitching motion with excellent correlation.[4,5] Okoroha et al and Makhni et al have shown the device to be 96.4% to 100% precise in detecting medial elbow torque during a fastball pitch,[20,23] and demonstrated it as a reliable method to measure stress parameters at the elbow.[5]

Participants were allowed to warm up their throwing arm using their typical routine. Players were then instructed to emulate live-game pitching. Once ready, pitchers were recorded throwing five consecutive fastball pitches at maximum effort. All pitches were thrown from the mound at a standard distance of 60 feet and 6 inches (18.4 meters). Pitches were considered erroneous and not counted towards data collection if the ball could not be reasonably stopped by the catcher. Ball velocity was recorded using a radar gun situated behind the player (Stalker Sport 2 radar gun, Stalker Radar) and recorded. Data output by the wearable sensor was recorded after every pitch and collected from the mobile phone application for analysis.

Statistical Analysis

All data are described using appropriate descriptive statistics including counts and percentages for categorical variables; means, medians, minimums, 25th percentile, 75th percentile, maximum, and standard deviation for non-repeated continuous variables. For the pitching measurements captured by the wearable sensor sleeve, least-squared (or adjusted) means and standard errors for each of the repeated pitching measurements were used as a more accurate way to describe repeated measurements than simply averaging all five measurements together, because this method adjusts for the correlation between measurements from the same pitcher and gives more accurate standard error estimates. The least-squared means and standard errors (SE) are used for continuous variables, and the odds ratios with 95% confidence intervals (CI) for categorical variables. Univariate repeated-measures mixed models used to describe the relationship between each pitching characteristic and each demographic variable. To compare demographic variables between outcome scores, Spearman's correlation coefficients, Wilcoxon rank-sum tests, and Kruskal-Wallis tests are used. These nonparametric tests are chosen due to the small group sizes and non-normal distributions. Statistical significance is set at $p<0.05$ and all analyses are carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA).

Results

Demographics

A total of 28 pitchers were included for final analysis in this study. The average [standard deviation] age and BMI was 20.1 [1.3] years and 23.9 [3.24] kg/m^2, respectively. Pitchers' average playing experience was 15.3 years, with 2.5 years at the college level. Thirteen pitchers were starters and 15 were relieving pitchers. No pitchers participated in formal live baseball games during the offseason preceding testing, however 26 of the 28 study participants participated in offseason bullpen practice. Prior to their college careers, 12 pitchers reported playing year-round baseball and 24 pitchers participated in multiple sports during high school. All but one pitcher reported that they routinely perform upper extremity stretches for prevention (96.4%). Table I illustrates pitcher demographics, arm length measurements, and preseason intake questionnaires.

Shoulder Range of Motion

Shoulder ROM is displayed in Table II. Dominant shoulder ER was significantly greater than non-dominant shoulder, 94° [10.37°] vs 88° [9.23°], respectively ($P < 0.05$). Dominant abduction, IR, and TROM were significantly less than non-dominant ($P < 0.05$). Average GIRD and ERG were 11° [9.9°] and 6° [8.8°], respectively.

Pitcher Factors Associated with Ball Velocity and Medial Stress

Table III illustrates the relationship of pitch velocity and elbow stress with pitcher demographics, arm length and shoulder ROM using univariate relationship analysis presented as beta estimates [standard error]. The least-squared (adjusted) means [standard errors] for velocity of fastballs was 76.5 [0.43] miles per hour (MPH) and mean medial elbow torque was of 46.1 [0.48] Nm. With regards to pitching velocity, univariate analysis revealed that for each addition 1-unit increase in BMI, 1-cm increase in upper arm length or elbow circumference, or 1 degree increase in shoulder ER, pitchers produced significantly greater ball velocity (beta estimates 0.61 [0.27], 0.36 [0.18], 1.28 [0.22], or 0.16 [0.06] MPH, respectively $P < 0.05$). With regards to medial elbow torque (elbow stress), univariate analysis revealed that each additional 1-degree increase in shoulder ER yielded a 0.35 [0.06] Nm increase in medial elbow torque (beta estimate, $P < 0.05$). With each additional 1cm increase in total or upper arm length there was a 0.36 [0.10] or 0.84 [0.19] Nm reduction in medial elbow stress (beta estimate, $P < 0.05$.

Pitching Sensor Measurements and Shoulder ROM

The average ball velocity, medial elbow torque, arm slot, arm speed, and shoulder rotation measured are illustrated in Table IV. Pitchers with GIRD ≥ 20°, compared to those with GIRD < 20°, demonstrated significantly reduced medial elbow torque (43.5 [1.1] vs 46.6 [0.5] Nm, $P = .011$) and significantly greater arm speed (924.3 [16.7] vs 883.2 [7.8] RPM, $P = .028$). Pitchers with ERG ≥ 5°, compared to those with ERG < 5°, demonstrated significantly increased medial elbow torque (47.4 [0.7] vs 45.1 [0.6] Nm, P = .014), consistent with the univariate analysis in Table III demonstrating significant correlation between medial elbow torque and ER. Pitchers with ERG ≥ 5° also demonstrated significantly reduced arm slot (37.7° [2.4°] vs 46.4° [2.1°], P = .007). Pitchers with loss of TROM ≥ 5°, compared to those with loss of TROM < 5°, demonstrated significantly reduced medial elbow torque (43.6 [1.1] vs 46.6 [0.5] Nm, P = .013), significantly reduced arm speed (848.6 [16.6] vs 899.8 [7.8] RPM, P = .006), and significantly increased shoulder rotation (157.2° [2.7°] vs 150.1° [1.2°], P = .018).

Discussion

Our study found that shoulder external rotation in collegiate pitchers is not only associated with increased ball velocity but also increased medial elbow torque. Additionally, pitchers with GIRD and a loss of TROM demonstrated reduced medial elbow torque. Increased arm length was protective of medial elbow torque, while no associations were found with other demographic characteristics. These findings indicate that in pitchers, gains in external rotation are associated with increased elbow stress and ball velocity, while decreased total range of motion is protective against elbow stress.

The late cocking and early acceleration phase of pitching occurs at the greatest degree of external rotation in the throwing shoulder and simultaneously produces a valgus medial elbow torque, primarily transmitted to the anterior bundle of the UCL.[10,12,13,28] Several studies have attempted to quantify the stress at the medial elbow throughout the pitching movement.[18,20,23-25] In an assessment of 20 youth pitchers using wearable sensor technology, Okoroha et al determined that fastballs and ball velocity were predictors of medial elbow torque, however the study did not analyze shoulder ROM.[23] In an older group of 23 high school pitchers with average

GIRD of 15.3° [11.2] degrees (35% of whom had GIRD > 20°), Smith et al corroborated prior findings that ball velocity was a predictor for increased torque, and interestingly found GIRD to have no association with medial elbow torque (P = .205).[29] However, the average age of the cohort of high school pitchers was 15.4 [1.03], potentially representing skeletally and physically immature pitchers. Additionally, in an analysis of 12 professional pitchers, Lizzio et al corroborated the finding that fastballs place the greatest torque across the medial elbow, but the authors did not incorporate shoulder ROM in their analysis.[19] Lastly, Camp et al also evaluated pitchers using wearable sensor technology, finding a positive correlation between shoulder rotation and medial elbow torque.[5] However, the authors did not directly measure shoulder ROM, but rather used shoulder rotation as measured by the sensor itself in their analysis. The current study evaluated collegiate pitchers of average age 20.14 [1.13] to assess predictors of medial elbow torque in an adult population. ERG was found to be predictive of increased medial elbow torque, while each additional degree of ER was found to increase medial elbow torque by 0.35 Nm and fastball velocity by 0.16 MPH. These results support prior biomechanical studies which have correlated maximal shoulder external rotation with the time of greatest elbow stress.[10,12,13] This suggests that increased external rotation in pitchers is adaptive in order to generate the greatest torque, and pitch speed, resulting in increased medial elbow stress.

The correlation between GIRD and elbow stress has been evaluated in prior studies. Smith and colleagues evaluated 23 high school athletes with an average age of 15.4 [1.03]. Their study found no significant association between GIRD (mean [SD]: 15.3° [11.2] degrees) and medial elbow torque (P = .205).[29] In a systemic review (Level IV) of the literature on GIRD and injuries in overhead throwing athletes, Johnson et al found that there was a statistically significant increase in rate of upper extremity injuries for athletes with pathological GIRD compared to those without it.[15] In a case control study, Dines et al showed that pitchers with UCL insufficiency had significantly greater GIRD (28.5° vs 12.7°, $P < .001$) and loss of TROM (133.5° vs 143.1°, $P = .027$) than healthy controls.[9] While the prior two studies found increased injury rate in pitchers with GIRD, no direct correlation was made between GIRD and elbow stress. The present study found that GIRD and loss of TROM were significantly associated with reduced medial elbow torque. These finding suggest that decrease range of motion in the shoulder may limit the development of arm speed and decrease medial elbow stress. This also illustrates the multifactorial etiology of elbow injuries, as GIRD has been implicated as predisposing to elbow injury in the literature, which may be due to other factors.[9,15,27] The present findings do not suggest that GIRD is protective of elbow injuries, but rather support the notion that medial elbow stress is maximized during extremes of external rotation and dampened in pitchers with global loss of motion.

Prior investigations have demonstrated that certain demographic characteristics are either predictive or protective of medial elbow torque, with contrary results. BMI was found to be associated with increased medial elbow torque in youth pitchers,[23] but reduced medial elbow torque in professional baseball pitchers.[19] In the present study, BMI was not found to be associated with medial elbow torque in collegiate pitchers. Likewise, increased arm length was found to be protective of medial elbow torque in youth pitchers,[23] but associated with increased medial elbow torque in high school pitchers,[29] and showed no association in professional pitchers.[19] Although college pitchers would be expected to demonstrate similar characteristics as professional pitchers, the results of the present study demonstrated that increased arm length was protective of medial elbow stress, similar to findings in youth pitchers.

In a descriptive study of 82,000 throws by professional baseball pitchers wearing sensor technology, Camp et al investigated the association between measurements by the sensor such as arm rotation, arm speed and arm slot, with the measurement of medial elbow torque.[5] They concluded that medial elbow torque was associated with increasing arm rotation and arm speed, but reduced arm slot using Chi-squared analysis. However, they did not measure pitchers' shoulder ROM or analyze maladaptation (ERG, GIRD, or loss of TRROM). Conversely, the present study did not find these three parameters measured by the wearable sensor to relate significantly to medial elbow torque in collegiate athletes using univariate least-squared means analysis. Methodologically, the sample size of throws in this study was comparatively much smaller. Theoretically, professional pitchers in the aforementioned study may not be generalizable to collegiate pitchers, who potentially possess different dynamic and physical attributes that become more well established in single-sport, year-round professional pitchers. Given that collegiate pitchers are not far removed from their multi-sport high school background, their lack of specialization relative to a professional athlete may confound these variables.

Limitations

This study does have important limitations. The study was conducted at multiple collegiate institutions which made standardization of pitcher practice frequency, duration, rehabilitation, and offseason regimens difficult. Additionally, although no formal live games took place during the preseason, pitching workload volume prior to study initiation could not be quantified, and presents a significant risk factor for each pitcher. Although an attempt was made to account for this limitation through pitcher intake forms, these forms may be subject to recall bias. Furthermore, the observational nature of the study presented a significant limitation, as pitchers were unable to be assessed on a more longitudinal basis to control for variability in measurements. It is impossible to determine if torque measured across the medial elbow is a true representation of the stress across the elbow UCL during pitching or a cumulative sum of forces across the medial elbow. However, the MOTUS sleeve has been used in multiple other studies as an accurate and reliable assessment of medial elbow stress.[4,5,20,23] Additionally, pitchers in the present study were evaluated at one time point, the preseason and due to this fact, extremes in shoulder and elbow pathology may not have developed yet, as they would during a season of pitching.[16,17] Lastly, while GIRD and loss of TROM yielded similar associations with medial elbow torque, and multivariate analysis was unable to determine if they are related given the small sample size.

Conclusion

College pitchers with increased external rotation produce greater medial elbow torque during the pitching movement. Each degree of increased external rotation was found to correlate with increased elbow torque and ball velocity. On the contrary, arm length and reduced shoulder range of motion were associated with reduced medial elbow torque. This study suggests that increased external rotation in pitchers is associated with greater elbow stress during pitching.

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Legends

Figure 1. Internal rotation measured with the subject supine. The shoulder is positioned to 90° abduction and elbow flexion with the forearm perpendicular to the floor in neutral position. To stabilize the scapula, posterior pressure is applied at the acromion. The subject then internally (pictured above) or externally rotates their arm to an endpoint. At this point, a second examiner employed a goniometer to record ROM.

Figure 2. Wearable baseball compression sleeve with a sensor device at the medial elbow. This sensor is placed inside a medial elbow pocket and outputs accelerometer and gyroscope data to be recorded by a mobile phone application (motusTHROW v 8.3.3; Motus Global). The wearable device records elbow torque (Newton meters, Nm), arm slot (degrees, deg), arm speed (rotations per minute, RPM), and shoulder rotation (deg). The device is placed so that the sensor rests 1.5 inches distal to the medial epicondyle of the humerus, as directed by the device manufacturer's instructions. The medial epicondyle is depicted by the circle on the sleeve.

Table I. Preseason Pitcher Demographics and Intake Survey

Continuous variables are presented as Mean [Standard Deviation]. Categorical variables are presented as Number (percentage)

Table II. Arm Length and Shoulder ROM Measurements

Measurements presented as Mean [Standard Deviation]. Abbreviations: Shoulder ROM, range of motion; ER, external rotation; IR, internal rotation; GIRD, glenohumeral internal rotation deficiency; ERG, external rotation gain; TROM, total range of motion. **Bold** values indicate statistical significance, P<0.05

Table III. Relationship of Pitcher-centric factors to Pitch Velocity and Medial Elbow Torque

Univariate Relationships for continuous variables are presented as beta estimates [Standard Error] and Pearson's Correlations are presented as r-values. Interpretation for beta estimates is as follows: for every 1-unit increase in a pitcher factor, the measurement increases or decreases by the magnitude of the beta estimate (i.e. every 1-degree increase in shoulder ER results in medial elbow torque increasing by 0.35; every 1-cm increase in total arm length results in medial elbow torque decreasing by 0.36). *Abbreviations:* ROM, range of motion; ER, external rotation; IR, internal rotation; GIRD, glenohumeral internal rotation deficiency; ERG, external rotation gain; TRROM, total rotational range of motion. **Bold** values indicate statistical significance, P<0.05

Table IV. Univariate Associations between Sensor Pitching Measurements and Shoulder Rotational Adaptations

Univariate associations between categorical variables are presented as adjusted Least-Squared Means [Standard Error]. *Abbreviations:* MPH, miles per hour; GIRD, glenohumeral internal rotation deficiency; ERG, external rotation gain; TRROM, total rotational range of motion. **Bold** values indicate statistical significance (P < 0.05)

Table I. Preseason Pitcher Demographics and Intake Survey

Pitcher Factors (n = 28)	Mean [SD]
Age	20.14 [1.3]
Height (cm)	186.4 [6.95]
Weight (kg)	83.1 [11.91]
BMI	23.9 [3.24]
Hand Dominance	
Right	21 (75%)
Pitching Role	
Starter	13 (46.4%)
Reliever/Closer	15 (53.6%)
College Year	
Freshman	7 (25%)
Sophomore	8 (28.6%)
Junior	8 (28.6%)
Senior	5 (17.9%)
Years Played Overall	15.25 [1.84]
NCAA II Experience	2.46 [1.20]
Dominant Arm Length (cm)	
Total Arm	78.0 [4.52]
Upper Arm	35.0 [2.44]
Lower Arm	30.0 [1.92]
Elbow Circumference	28.0 [1.77]
Workload History	
Bullpen Practice in Offseason	26 (92.9%)
1-3 times/week	23 (82.1%)
4-6 times/week	3 (10.7%)
High School History	

Year-Round Baseball	12 (42.9%)
Multi-sport Athlete	24 (85.7%)
Currently involved in Stretching Program	27 (96.4%)

Continuous variables are presented as Mean [Standard Deviation]

Categorical variables are presented as Number (percentage)

Table II. Arm Length and Shoulder ROM Measurements

Shoulder ROM (degrees)	Dominant	Non-Dominant	P-Value
Forward Flexion	142.0 [7.63]	142.0 [8.90]	0.082
Abduction	138.0 [6.86]	140.0 [7.29]	**<.001**
ER	94.0 [10.37]	88.0 [9.23]	**<.001**
IR	55.0 [10.63]	66.0 [9.12]	**<.001**
TROM	149.0 [12.41]	154.0 [10.6]	**<.001**
GIRD	11.0 [9.87]		
ERG	6.0 [8.77]		

Measurements presented as Mean [Standard Deviation]

ROM, range of motion; ER, external rotation; IR, internal rotation; GIRD, glenohumeral internal rotation deficiency; ERG, external rotation gain; TROM, total range of motion.

Bold text indicates statistical significance, P<0.05

Table III. Relationship of Pitcher-centric factors to Pitch Velocity and Medial Elbow Torque

Pitcher Factors	MPH 76.5 [0.43]		Elbow Stress 46.1 [0.48]	
	Univariate Relationship	*r-value*	*Univariate Relationship*	*r-value*
Age	0.64 [0.72]		1.13 [0.71]	
Height	-0.11 [0.13]		-0.20 [0.13]	
Weight	0.12 [0.07]		-0.14 [0.08]	
BMI	**0.61 [0.27]**		-0.31 [0.29]	
Arm Length (cm)				
Total Arm	-0.01 (0.10)		**-0.36 (0.10)**	**-0.27**
Upper Arm	**0.36 (0.18)**	**0.24**	**-0.84 (0.19)**	**-0.32**
Lower Arm	-0.28 (0.23)		-0.15 (0.26)	
Elbow Circumference	**1.28 (0.22)**	**0.43**	-0.41 (0.27)	
Shoulder ROM (degrees)				
ER	**0.16 (0.06)**	**0.25**	**0.35 (0.06)**	**0.45**
IR	-0.02 (0.04)		0.08 (0.05)	
GIRD	-0.05 (0.04)		-0.04 (0.05)	
ERG	-0.03 (0.15)		-0.03 (0.11)	
TROM	-0.02 (0.17)		0.06 (0.08)	
MPH	-		0.14 (0.15)	
Arm Slot	0.20 (0.50)		0.02 (0.03)	
Arm Speed	1.08 (2.30)		-0.001 (0.01)	
Arm Rotation	-		-0.03 (0.04)	

Univariate Relationships for continuous variables are presented as beta estimates [Standard Error] and Pearson's Correlations are presented as r-values

Interpretation for beta estimates is as follows: for every 1-unit increase in a pitcher factor, the measurement increases or decreases by the magnitude of the beta estimate (i.e. every 1-degree increase in shoulder ER results in medial elbow torque increasing by 0.35; every 1-cm increase in total arm length results in medial elbow torque decreasing by 0.36).

Abbreviations: ROM, range of motion; ER, external rotation; IR, internal rotation; GIRD, glenohumeral internal rotation deficiency; ERG, external rotation gain; TROM, total range of motion.

Bold indicates statistical significance, P<0.05

Table IV. Univariate Associations between Sensor Pitching Measurements and Shoulder Rotational Adaptations

	Elbow Stress	P-value	Arm Slot	P-value	Arm Speed	P-value	Shoulder Rotation	P-value
	46.1 [0.48]		42.7 [1.64]		890.6 [7.25]		151.4 [1.16]	
Shoulder ROM								
GIRD								
<20	46.6 [0.5]	**P=.011**	43.6 [1.8]	P=.232	883.2 [7.8]	**P=.028**	152.1 [1.3]	P=.223
≥20	43.5 [1.1]		38.5 [3.8]		924.3 [16.7]		14.4 [2.7]	
ERG								
<5	45.1 [0.6]	**P=.014**	46.4 [2.1]	**P=.007**	898.4 [9.5]	P=.214	151.7 [1.5]	P=.81
≥*5*	47.4 [0.7]		37.7 [2.4]		880.3 [10.9]		151.1 [1.8]	
Loss TROM								
<5	46.6 [0.5]	**P=.013**	43.3 [1.8]	P=.44	899.8 [7.8]	**P=.006**	150.1 [1.2]	**P=.018**
≥*5*	43.6 [1.1]		40.0 [3.9]		848.6 [16.6]		157.2 [2.7]	

Univariate associations between categorical variables are presented as adjusted Least-Squared Means [Standard Error]

Abbreviations: MPH, miles per hour; GIRD, glenohumeral internal rotation deficiency; ERG, external rotation gain; TROM, total range of motion.

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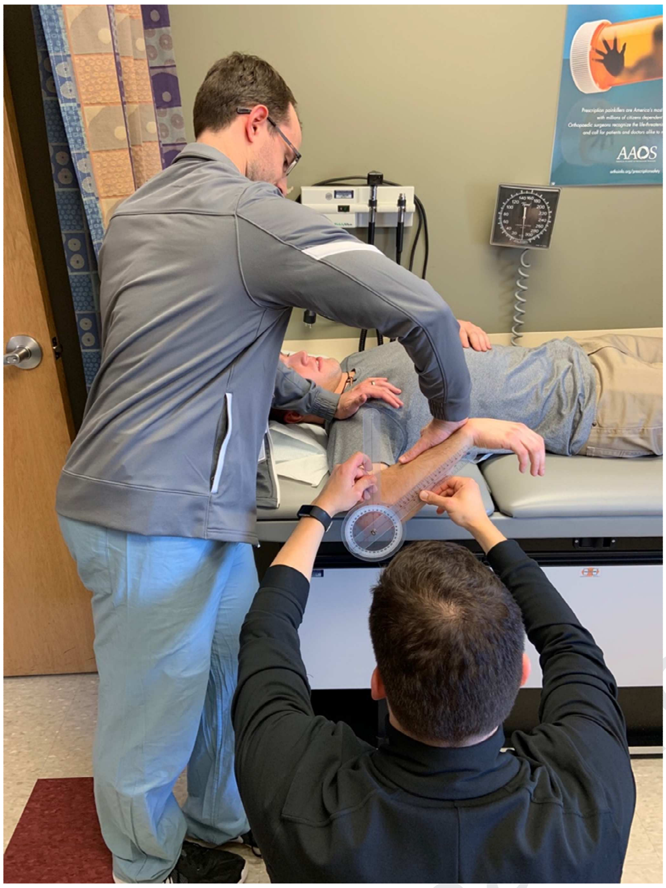

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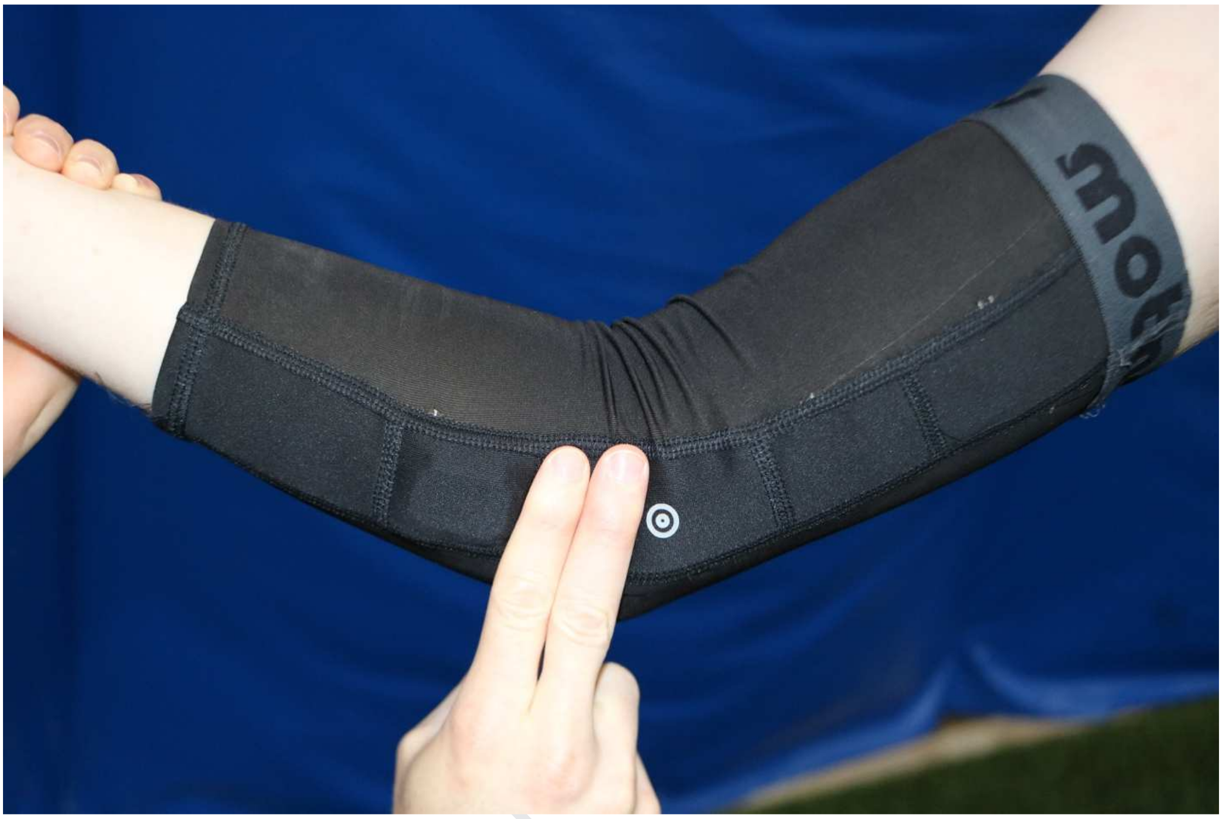

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