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The relationship between shoulder range of motion and elbow stress in college pitchers

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

Methods: Pitchers were recruited from 3 college baseball teams. Players with prior injury or on pitching restrictions because of pain were excluded. Players were evaluated within 2 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 that 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 warm-up, pitchers threw 5 fastballs in a standardized manner off the mound at game-speed effort. The primary outcome evaluated the relationship between shoulder ROM and medial elbow torque. Additional outcomes evaluated pitcher characteristics and demographic characteristics in the context of shoulder ROM.

Results: Twenty-eight pitchers were included in the preseason analysis. The average age and playing experience were 20.1 years (standard deviation [SD], 1.3 years) and 15.3 years (SD, 1.8 years), respectively, with 2.5 years (SD, 1.2 years) playing at collegiate level. The dominant shoulder showed decreased internal rotation and increased external rotation (ER) relative to the nondominant side ($P < .001$). The average glenohumeral internal rotation deficit and ERG were 11.3° (SD, 9.87°) and 5.71° (SD, 8.8°), respectively. ERG $\geq$ 5° was a significant predictor of elbow stress during pitching (47.4 Nm [SD, 0.7 Nm] vs. 45.1 Nm [SD, 0.6 Nm], $P = .014$). Univariate associations showed that each additional degree of ER resulted in increased elbow torque (β estimate, 0.35 ± 0.06 Nm; $P = .003$). Conversely, decreased medial elbow torque was found in pitchers with reduced shoulder ROM (glenohumeral internal rotation deficit $\geq$ 20°: 43.5 Nm [SD, 1.1 Nm] vs. 46.6 Nm [SD, 0.5 Nm], $P = .011$; loss of total rotational ROM $\geq$ 5°: 43.6 Nm [SD, 1.1 Nm] vs. 46.6 Nm [SD, 0.5 Nm], $P = .013$) and in those with greater arm length ($P < .05$).

Conclusions: College pitchers with increased ER produce greater medial elbow torque during the pitching movement. Each degree of increased ER was found to correlate with increased elbow torque and ball velocity. On the contrary, arm length and reduced shoulder ROM were associated with reduced medial elbow torque. This study suggests that increased ER 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

This project was reviewed and approved by the institutional review board at Henry Ford Hospital (no. 12481), the main institution of the attending physician conducting the research.

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Overhead athletes, particularly baseball pitchers, are at risk of upper-extremity injuries throughout their careers.[15] Among these injuries, 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).[26] It has been proposed that GIRD > 20°, ERG > 5°, and loss of TROM > 5° represent pathologic shoulder ROM adaptations,[14,26] which may predict an increased risk of elbow injury.[26]

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 shown that the maximal opening stress at the medial elbow occurs during the late cocking and early acceleration phases of pitching, at which point the shoulder is at its maximal point of external rotation (ER).[10,12,13] The increased volume and repetitive nature of overhead throwing in baseball pitchers eventually lead to downstream adaptive changes,[6] such as increased ulnar collateral ligament (UCL) thickness and elbow laxity.[2,3,7,11,16,20,21] These adaptations may indicate increased risk of elbow injury,[11] whereas resolution of these adaptations appears 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.[5,18,19,22,24,25,28] In youth, high school, and professional pitchers, fastballs and ball velocity have been implicated as predictors of medial elbow torque.[18,22,28] In high school pitchers, GIRD was interestingly determined to be protective against medial elbow torque; however, this cohort's average age was 15.4 years (standard deviation [SD], 1.03 years), and the data may not be generalizable to physically mature adults.[28] Despite the understanding of normal shoulder biomechanics during the pitching motion, it remains unclear how adult pitchers' adaptive shoulder ROM (ie, GIRD and ERG) is associated with stress at the medial elbow.

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

Methods

This was a prospective observational study of shoulder ROM deficits as predictors of medial elbow torque during throwing in Division II National Collegiate Athletic Association college pitchers. Each participant gave informed consent prior to data collection. The wearable-sensor technology and vendor were not involved in funding or designing this study. Pitchers from 3 Division II National Collegiate Athletic Association universities were eligible for consideration in this study. Players aged ≥ 18 years who described their primary position as pitcher were included. The 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 declined to participate during the recruitment phase. Of the 30 pitchers who elected to participate, 2 were excluded from the study because of 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 2 weeks prior to the first game of the season. 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 measured 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 those in previous studies implementing a wearable-sensor device.[22]

Shoulder ROM was recorded prior to any throwing at the practice sessions. ROM measurements included both dominant and nondominant shoulder abduction, forward flexion, neutral ER, and supine internal rotation (IR) and ER in abduction. Shoulder forward flexion and abduction were recorded by having the subject stand upright, with one examiner behind the subject stabilizing the scapula and instructing the subject to elevate the arm to end ROM, at which point a second examiner used a goniometer to record ROM in degrees. For supine IR and ER in abduction, the participant was instructed to lie supine on an examination table. The shoulder was then positioned to 90° of 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 the arm to end ROM while a second examiner used a goniometer to record internal and external ROM (Fig. 1). ROM of both upper extremities was measured in every study subject in standardized fashion by the same 2 investigators.

Shoulder ROM was further categorized in terms of GIRD, ERG, and loss of TROM, which was calculated between the dominant and nondominant shoulders, consistently with the

Figure 1 Internal rotation measured with subject supine. The shoulder is positioned to 90° of 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 rotates (as shown) or externally rotates the arm to an endpoint. At this point, a second examiner uses a goniometer to record range of motion.

Figure 2 Wearable baseball compression sleeve with sensor device at medial elbow. The sensor is placed inside a medial elbow pocket and outputs accelerometer and gyroscope data to be recorded by a mobile phone application (motusTHROW, version 8.3.3). The wearable device records elbow torque (in newton meters), arm slot (in degrees), arm speed (in rotations per minute), and shoulder rotation (in degrees). The device is placed so that the sensor rests 3.81 cm (1.5 in) 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.

literature.[26] GIRD was defined as the IR of the dominant shoulder subtracted from the IR of the nondominant shoulder. ERG was defined as the ER of the nondominant shoulder subtracted from the ER of 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 nondominant shoulder. For the purposes of statistical analysis, shoulder ROM was analyzed as a continuous variable, whereas pitchers with GIRD $\geq$ 20°, ERG $\geq$ 5°, and loss of TROM $\geq$ 5° were compared with pitchers without them in a separate analysis.

Pitching data were 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, version 8.3.3; Motus Global, Rockville Centre, NY, USA). The wearable device records elbow torque (in newton meters), arm slot (in degrees), arm speed (in rotations per minute [rpm]), and shoulder rotation (in degrees). The device was consistently placed so that the sensor rested 3.81 cm (1.5 in) distal to the medial epicondyle of the humerus, as directed by the device manufacturer's instructions (Fig. 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 and showed an excellent correlation.[4,5] Okoroha et al[22] and Makhni et al[19] have shown the device to be 96.4% to 100% precise in detecting medial elbow torque during a fastball pitch and to be a reliable method to measure stress parameters at the elbow.[5]

Participants were allowed to warm up the throwing arm using their typical routine. They were then instructed to emulate live-game pitching. Once ready, pitchers were recorded throwing 5 consecutive fastball pitches at maximum effort. All pitches were thrown from the mound at a standard distance of 18.4 m (60 ft 6 in). Pitches were considered erroneous and not counted toward 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, Richardson, TX, USA). Data output by the wearable sensor was recorded after every pitch and collected from the mobile phone application for analysis.

Statistical analysis

All data were described using appropriate descriptive statistics including count and percentage for categorical variables and mean, median, minimum, 25th percentile, 75th percentile, maximum, and standard deviation for non-repeated continuous variables. For the pitching measurements captured by the wearable-sensor sleeve, least squares (or adjusted) means and standard errors (SEs) for each of the repeated pitching measurements were used as a more accurate way to describe repeated measurements than simply averaging all 5 measurements together, because this method adjusted for the correlation between measurements from the same pitcher and gave more accurate SE estimates. Least squares means and SEs were used for continuous variables, whereas odds ratios and 95% confidence intervals were used for

Table I Preseason pitcher demographic characteristics and intake survey data

Pitcher factor	Data (N = 28)
Age, yr	20.14 [1.3]
Height, cm	186.4 [6.95]
Weight, kg	83.1 [11.91]
BMI, kg/m^2	23.9 [3.24]
Right hand dominance	21 (75)
Pitching role	
Starter	13 (46.4)
Reliever or 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, yr	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, cm	28.0 [1.77]
Workload history	
Bullpen practice in off-season	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)
Multiple-sport athlete	24 (85.7)
Currently involved in stretching program	27 (96.4)

BMI, body mass index; *NCAA*, National Collegiate Athletic Association. Continuous variables are presented as mean [standard deviation], whereas categorical variables are presented as number (percentage).

categorical variables. Univariate repeated-measures mixed models were used to describe the relationship between each pitching characteristic and each demographic variable. Spearman correlation coefficients, the Wilcoxon rank sum test, and the Kruskal-Wallis test were used to compare demographic variables between outcome scores. These nonparametric tests were chosen because of the small group sizes and non-normal distributions. Statistical significance was set at $P < .05$, and all analyses were carried out using SAS software (version 9.4; SAS Institute, Cary, NC, USA).

Results

Demographic characteristics

A total of 28 pitchers were included for final analysis in this study. The average age and BMI were 20.1 years (SD, 1.3 years) and 23.9 kg/m^2 (SD, 3.24 kg/m^2), respectively. Pitchers' average playing experience was 15.3 years, with 2.5 years at the college level. Of the pitchers, 13 were starters and 15 were "relievers or closers". No pitchers participated in formal live baseball games during the off-season preceding testing; however, 26 of the 28 study pitchers participated in off-season 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 1 pitcher (96.4%) reported routinely performing upper-extremity stretches for prevention. Table I presents pitcher demographic characteristics, arm length measurements, and preseason intake questionnaires.

Shoulder ROM

Shoulder ROM is displayed in Table II. Dominant-shoulder ER was significantly greater than nondominant-shoulder ER ($P < .05$): 94° (SD, 10.37°) vs. 88° (SD, 9.23°). Dominant-shoulder abduction, IR, and TROM were significantly less than nondominant-shoulder abduction, IR, and TROM ($P < .05$). Average GIRD and ERG measured 11° (SD, 9.9°) and 6° (SD, 8.8°), respectively.

Pitcher factors associated with ball velocity and medial stress

Table III presents the relationship of pitch velocity and elbow stress with pitcher demographic characteristics, arm length, and shoulder ROM using univariate relationship analysis presented as β estimates (with SEs). The least squares (adjusted) mean for fastball velocity was 76.5 miles per hour (mph) (SE, 0.43 mph), and mean medial elbow torque was 46.1 Nm (SE, 0.48 Nm). Regarding pitching velocity, univariate analysis revealed that for each 1-unit increase in BMI, 1-cm increase in upper arm length, 1-cm increase in elbow circumference, and 1° increase in shoulder ER, pitchers produced significantly greater ball velocity (β estimates of 0.61 mph [SE, 0.27 mph], 0.36 mph [SE, 0.18 mph], 1.28 mph [SE, 0.22 mph], and 0.16 mph [SE, 0.06 mph], respectively; $P < .05$). Regarding medial elbow torque (elbow stress), univariate analysis revealed that each 1-degree increase in shoulder ER yielded an increase in medial elbow torque of 0.35 Nm (SE, 0.06 Nm; β estimate, $P < .05$). With each 1-cm increase in total or upper arm length, a reduction in medial elbow stress of 0.36 Nm (SE, 0.10 Nm) or 0.84 Nm (SE, 0.19 Nm) occurred (β estimate, $P < .05$).

Pitching sensor measurements and shoulder ROM

The average ball velocity, medial elbow torque, arm slot, arm speed, and shoulder rotation measured are presented in Table IV. Compared with pitchers with GIRD < 20°, those with GIRD ≥ 20° showed significantly reduced medial

Table II Arm length and shoulder ROM measurements

Shoulder ROM	Dominant, °	Nondominant, °	*P* value
Forward flexion	142.0 [7.63]	142.0 [8.90]	.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]		

Data are presented as mean [standard deviation].
ROM, range of motion; *ER*, external rotation; *IR*, internal rotation; *TROM*, total range of motion; *GIRD*, glenohumeral internal rotation deficiency; *ERG*, external rotation gain.
* Statistically significant ($P < .05$).

elbow torque (43.5 Nm [SE, 1.1 Nm] vs. 46.6 Nm [SE, 0.5 Nm], $P = .011$) and significantly greater arm speed (924.3 rpm [SE, 16.7 rpm] vs. 883.2 rpm [SE, 7.8 rpm], $P = .028$). Pitchers with ERG ≥ 5° showed significantly increased medial elbow torque compared with those with ERG < 5° (47.4 Nm [SE, 0.7 Nm] vs. 45.1 Nm [SE, 0.6 Nm], $P = .014$), consistently with the univariate analysis in Table III showing a significant correlation between medial elbow torque and ER. Pitchers with ERG ≥ 5° also showed a significantly reduced arm slot (37.7° [SE, 2.4°] vs. 46.4° [SE, 2.1°], $P = .007$). Compared with pitchers with loss of TROM < 5°, those with loss of TROM ≥ 5° showed significantly reduced medial elbow torque (43.6 Nm [SE, 1.1 Nm] vs. 46.6 Nm [SE, 0.5 Nm], $P = .013$), significantly reduced arm speed (848.6 rpm [SE, 16.6 rpm] vs. 899.8 rpm [SE, 7.8 rpm], $P = .006$), and significantly increased shoulder rotation (157.2° [SE, 2.7°] vs. 150.1° [SE, 1.2°], $P = .018$).

Discussion

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

The late cocking and early acceleration phases of pitching occur at the greatest degree of ER in the throwing shoulder and simultaneously produce a valgus medial elbow torque, primarily transmitted to the anterior bundle of the UCL.[10,12,13,27] Several studies have attempted to quantify the stress at the medial elbow throughout the pitching movement.[18,19,22-24] In an assessment of 20 youth pitchers using wearable-sensor technology, Okoroha et al[22] determined that fastballs and ball velocity were predictors of medial elbow torque; however, the study did not analyze shoulder ROM. In an older group of 23 high school pitchers with average GIRD of 15.3° (SD, 11.2°) (35% of whom had GIRD > 20°), Smith et al[28] corroborated prior findings that ball velocity was a predictor of increased torque and interestingly found GIRD to have no association with medial elbow torque ($P = .205$). However, the average age of the cohort of high school pitchers was 15.4 years (SD, 1.03 years), potentially representing skeletally and physically immature pitchers. Additionally, in an analysis of 12 professional pitchers, Lizzio et al[18] corroborated the finding that fastballs place the greatest torque across the medial elbow, but they did not incorporate shoulder ROM in their analysis. Finally, Camp et al[5] evaluated pitchers using wearable-sensor technology and found a positive correlation between shoulder rotation and medial elbow torque. However, they did not directly measure shoulder ROM but rather used shoulder rotation as measured by the sensor itself in their analysis. Our study evaluated collegiate pitchers with an average age of 20.14 years (SD, 1.3 years) to assess predictors of medial elbow torque in an adult population. ERG was found to be predictive of increased medial elbow torque, whereas 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 the findings of prior biomechanical studies that have correlated maximal shoulder ER with the time of greatest elbow stress.[10,12,13] This finding suggests that increased ER in pitchers is adaptive to generate the greatest torque, as well as pitch speed, resulting in increased medial elbow stress.

The correlation between GIRD and elbow stress has been evaluated in prior studies. Smith et al[28] evaluated 23 high school athletes with an average age of 15.4 years (SD, 1.03 years). Their study found no significant association between GIRD (mean, 15.3° [SD, 11.2°]) and medial elbow torque ($P = .205$).[28] In a systemic review (level IV) of the literature on GIRD and injuries in overhead throwing athletes, Johnson et al[15] found a statistically significant increase in the rate of upper-extremity injuries in athletes with pathologic GIRD compared with those without it. In a case-control study, Dines et al[9] 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. Although the prior 2 studies found an increased injury rate in pitchers with GIRD, no direct correlation was made between GIRD and elbow stress. Our study found that GIRD and loss of TROM were significantly associated with reduced medial elbow torque. These findings suggest that decreased ROM in the shoulder may limit the development of arm speed and decrease medial elbow stress. They also illustrate the multifactorial etiology of elbow injuries, as GIRD has been

Table III Relationship of pitcher-centric factors to pitch velocity and medial elbow torque

Pitcher factor	Pitch velocity of 76.5 mph [SE, 0.43 mph]		Medial elbow torque: elbow stress of 46.1 Nm [SE, 0.48 Nm]	
	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				
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				
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)	
Miles per hour	—		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)	

mph, miles per hour; *SE*, standard error; *BMI*, body mass index; *ROM*, range of motion; *ER*, external rotation; *IR*, internal rotation; *GIRD*, glenohumeral internal rotation deficiency; *ERG*, external rotation gain; *TROM*, total range of motion.
Univariate relationships for continuous variables are presented as β estimate [SE], and Pearson correlations are presented as *r* values. Interpretation of β estimates is as follows: For every 1-unit increase in a pitcher factor, the measurement increases or decreases by the magnitude of the β estimate (ie, every 1° increase in shoulder ER results in medial elbow torque increasing by 0.35 Nm; every 1-cm increase in total arm length results in medial elbow torque decreasing by 0.36 Nm).
* Statistically significant ($P < .05$).

Table IV Univariate associations between sensor pitching measurements and shoulder rotational adaptations

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

SE, standard error; *ROM*, range of motion; *GIRD*, glenohumeral internal rotation deficiency; *ERG*, external rotation gain; *TROM*, total range of motion.
Univariate associations between categorical variables are presented as adjusted least squares mean [SE].
* Statistically significant ($P < .05$).

implicated as predisposing to elbow injury in the literature, which may be due to other factors.[9,15,26] 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 ER and dampened in pitchers with global loss of motion.

Prior investigations have shown 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 [22] but reduced medial elbow torque in professional baseball pitchers.[18] In our study, BMI was not associated with medial elbow torque in collegiate pitchers. Likewise, increased arm length was found to be protective of medial elbow torque in youth pitchers [22] but associated with increased medial elbow torque in high school pitchers, [28] whereas no association was shown in professional pitchers.[18] Although college pitchers would be expected to demonstrate similar characteristics to those of professional pitchers, the results of our study showed 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[5] investigated the association between measurements by the sensor, such as arm rotation, arm speed, and arm slot, and the measurement of medial elbow torque. They concluded that medial elbow torque was associated with increased arm rotation and arm speed but reduced arm slot using χ^2 analysis. However, they did not measure pitchers' shoulder ROM or analyze maladaptation (ERG, GIRD, or loss of total rotational ROM). Conversely, our study did not find the aforementioned 3 parameters measured by the wearable sensor to relate significantly to medial elbow torque in collegiate athletes using univariate analysis of least squares means. 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 multiple-sport high school backgrounds, their lack of specialization relative to a professional athlete may confound these variables.

Limitations

This study does have important limitations. It was conducted at multiple collegiate institutions, which made standardization of pitcher practice frequency, duration, rehabilitation, and off-season 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 whether 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 Global sleeve has been used in multiple other studies as an accurate and reliable assessment of medial elbow stress.[4,5,19,22] In addition, pitchers in this study were evaluated at 1 time point, the preseason, and owing to this fact, extremes in shoulder and elbow pathology may not have developed yet, as they would during a season of pitching.[16,17] Finally, although GIRD and loss of TROM yielded similar associations with medial elbow torque, multivariate analysis was unable to determine whether they are related given the small sample size.

Conclusion

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

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