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Limited Total Arc Glenohumeral Rotation and Shoulder Biomechanics During Baseball Pitching

Tomohiro Ide, MA, ATC*; Tyler J. Hamer, PhD†; Adam B. Rosen, PhD, ATC*; Colleen Vogel, MS, ATC‡; Dimitri Haan, BS§; Brian A. Knarr, PhD§; Samuel J. Wilkins, PhD, ATC*

*School of Health and Kinesiology, University of Nebraska at Omaha; †The Performance Technology Department, New York Mets; ‡Department of Kinesiology and Community Health, University of Illinois Urbana-Champaign; §Department of Biomechanics, University of Nebraska at Omaha

Context: Upper extremity injuries in baseball pitchers cause significant time loss from competing and decreased quality of life. Although shoulder range of motion (ROM) is reported as a key factor to prevent potential injury, it remains unclear how limited glenohumeral ROM affects pitching biomechanics which may contribute to upper extremity injuries.

Objective: To investigate how pitchers with decreased total arc glenohumeral ROM of the throwing arm differed in upper extremity pitching kinematics and kinetics as well as ball velocity compared with pitchers with greater levels of glenohumeral ROM.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Fifty-seven baseball pitchers (ages 18–24) were divided into either control ($\geq$160° total arc) or lower ROM ($<$160° total arc) groups.

Main Outcome Measure(s): The mean glenohumeral ROM deficits, pitching kinematic and kinetic outcomes, and ball velocity were compared between groups.

Results: The control group demonstrated significantly less deficit in total arc ROM between arms than the lower ROM (control: $-1.5° \pm 10.0°$; lower ROM: $-12.4° \pm 13.9°$; $P <$ .001). While the lower ROM group displayed less maximal shoulder external rotation (ER) while pitching, the control group had significantly less difference in ROM between maximal shoulder ER while pitching and clinically measured ER (lower ROM: $64.4° \pm 12.1°$; control: $55.8° \pm 16.6°$; $P =$ .025). The control group had significantly faster ball velocity than the lower ROM group (control: 85.0 $\pm$ 4.3 mph; lower ROM: 82.4 $\pm$ 4.8 mph; $P =$ .024).

Conclusion: Pitchers with decreased total arc glenohumeral ROM ($<$160° total arc) may undergo overstretching toward ER in the shoulder during the late cocking phase. Pitchers with higher total arc ROM can pitch the same or faster ball without increasing loading in the upper extremity. Total arc glenohumeral ROM measurement can be a clinical screening tool to monitor shoulder condition over the time, and pitchers with limited total arc ROM might be at higher risk of shoulder injury.

Key Words: upper extremity, injury prevention, clinical screening, motion capture

Key Points

- Pitchers in the lower range of motion (ROM) group separated by glenohumeral total arc ROM demonstrated greater deficits in both external rotation(ER) and internal rotation than the control group.
- Pitchers with $\geq$160° glenohumeral total arc ROM demonstrated less difference in ROM between maximal shoulder ER while pitching and clinically measured ER in the shoulder (lower ROM: $64.4° \pm 12.1°$; control: $55.8° \pm 16.6°$; $P =$ .025) with faster ball velocity, but no difference in shoulder and elbow kinetics was found between the groups.
- Athletic trainers may evaluate glenohumeral total arc ROM to identify pitchers with higher risk of shoulder injuries and can use the objective measurement to initiate early preventive interventions and track arm health over time.

Baseball pitching mechanics consist of 6 phases, including the wind-up, stride, late cocking, acceleration, deceleration, and follow-through phases.[1] The late cocking, acceleration, and deceleration phases are the most stressful phases in the upper extremity because the shoulder and elbow undergo the greatest joint loading and maximal range of motion (ROM).[2] Specifically, the ulnar collateral ligament of the elbow, labrum, rotator cuff, and the joint capsule of the shoulder are susceptible to stress and potential injury during these phases.[3–6]

To throw a baseball with increased velocity while decreasing the risk of injury, the kinetic chain must be efficient in each of its phases. The rapid rotational sequence of the body leads distal structures to temporally lag behind the proximal segments during the late cocking phase. The sequential rotation creates an effective transition of momentum to the throwing hand and allows pitchers to pitch a ball fast. Simultaneously, the sequence exposes the shoulder to the greatest maximal shoulder external rotation (ER), which exceed the clinically measured ER and the elbow to the highest valgus torque around 120 Nm.[7,8] Both the maximal shoulder ER and the valgus torque while pitching are positively associated with faster ball velocity, and ball velocity is the most common way to value a pitcher.[9,10]

Pitching mechanics and ball velocity have been linked to a variety of upper extremity injuries and ulnar collateral ligament sprains of the elbow and superior labrum anterior-posterior (SLAP) tears of the shoulder.[2,3,10] Because of concerns for injury risks, authors of several studies have attempted to understand the underlying causes of upper extremity injury, with shoulder ROM as a major interest for researchers and clinicians.[11–14] To date, limited total arc glenohumeral ROM, internal rotation (IR), and ER measured in clinical evaluation have been reported as risk factors for injury.[14] For instance, pitchers with limited total arc glenohumeral ROM demonstrated a higher risk of elbow injuries, but the physical characteristics may be modifiable using a variety of therapeutic interventions.[11,15] Thus, identification of such modifiable risk factors has been essential for injury risk mitigation. Recently, Bullock et al conducted a meta-analysis to understand shoulder ROM and baseball arm injuries and suggested 160° of total arc glenohumeral ROM could be a baseline for clinical screening to decrease the risk of upper extremity injuries.[14] While it may be informative for clinicians to recognize a specific objective threshold for risk of injury, the behavioral aspect of how a limited total arc glenohumeral ROM may affect pitching biomechanics remains unclear. Understanding how this baseline relates to pitching mechanics is clinically meaningful to provide proper suggestions for pitchers and for clinicians to effectively implement therapeutic intervention. Therefore, the purpose of this study was to investigate differences in baseball pitchers with lower total arc glenohumeral ROM compared with pitchers with higher total arc ROM. Specifically, we aimed to examine if lower levels of total arc ROM demonstrated differences in shoulder characteristics and its effect on joint loading of the throwing shoulder and elbow as well as ball velocity. First, we hypothesized that pitchers with limited total arc ROM would display greater deficits between dominant and nondominant arms. Secondly, we hypothesized that pitchers with optimal total arc ROM would experience lower levels of joint loading, including IR torque and distraction force in the shoulder and valgus torque in the elbow, demonstrate less difference between maximal shoulder ER while pitching and clinically measured shoulder ER (MaxERDiff) with no difference in ball velocity than those with limited total arc ROM. We also investigated other shoulder and elbow characteristics considered risk factors for injury and performance factors, including elbow flexion angle at the late cocking phase and shoulder horizontal abduction at the stride phase.[2,7,16] We expected that our findings would facilitate clinicians to provide concise recommendations for baseball pitchers and enhance the quality of health care based on total arc glenohumeral ROM evaluated in clinical screening.

METHODS

Experimental Approach and Study Design

A cross-sectional retrospective study design with convenience sampling was used for this study. Data were gathered from September 2021 to April 2023. We used data of pitchers who were recruited through athletic trainers or visited the pitching laboratory to be evaluated for clinical assessments and a 3-dimentional pitching motion analysis. This study was approved by the University of Nebraska Medical Center Institutional Review Board, and participants completed consent documentation before participating in data collection.

Participants

Participants included collegiate baseball pitchers and 1 semipro baseball pitcher between 18 and 24 years old who were healthy and cleared to throw at the time of evaluation. Pitchers with a history of shoulder or elbow surgeries were included if they were cleared by their physicians and fully returned to compete. Accordingly, participants were excluded if they had an ongoing injury with their upper extremities.

Procedures

Participants were evaluated using both clinical and biomechanics pitching evaluations on the same day. Participants first answered a custom demographics questionnaire, including age, weight, height, and hand dominance before beginning with the clinical evaluation. All clinical measurements were performed before participants warmed up for the pitching biomechanical evaluation. Glenohumeral ROM for the throwing and nonthrowing arms were measured by 2 clinicians with a standard goniometer. Participants were positioned supine on a standard plinth, and the shoulder was abducted at 90° with elbow flexed at 90°. The upper arm was maintained parallel to the table so that the shoulder was not horizontally abducted. To measure IR, the anterior shoulder was stabilized, and the arm was rotated internally until a firm end feel was noted (Figure 1).[17] After measuring IR, the evaluators measured ER with the participant in a similar position. However, instead of an anterior stabilization, the lateral border of the scapula was stabilized by the clinician's hand before moving the arm externally to achieve a firm end feel. The ER and IR values were added to determine the total arc glenohumeral ROM for both the dominant and nondominant arms. Each measurement was conducted once, and the peak-end ROMs were used for data analysis.

After the clinical evaluation, 41 reflective markers were placed on bony landmarks of the body.[18] A 20-high-speed-camera motion analysis system was used with sampling at 320 Hz (Qualisys AB). After the markers were placed, participants warmed up using their own self-prescribed routine. Participants threw a baseball from a custom instrumented force plate (Bertec) pitching mound toward a frame object placed at 17 m away in the pitching laboratory, with force plate sampling frequency set at 1280 Hz. Participants pitched roughly 20 balls during the pitching evaluation, and approximately 10 of those pitches were 4-seam fastballs. The markers were tracked in Qualisys Track Manager before being exported through the project automation framework. Tracked markers were attenuated by a low pass 6th-order Butterworth filter with a cutoff frequency of 20 Hz. Kinematic outcomes were measured at stride and late cocking phases, and kinetic outcomes were evaluated at the late cocking and deceleration phases. The stride

Figure 1. Clinical evaluation for glenohumeral internal rotation by 2 clinicians using a standard goniometer.

phase was determined as the time that the stride foot fully contacted the pitching mound, and the late cocking was defined as the moment of the throwing shoulder reaching maximal shoulder ER (Figure 2). Kinematic and kinetic outcomes included maximal shoulder ER (°), horizontal abduction (°) at the stride, elbow flexion angle (°) at the late cocking, peak shoulder distraction force (BW%), peak IR torque (Nm), and peak elbow valgus torque (Nm).

Data Analysis

Biomechanical variables were extracted from the report system of motion analysis (Qualisys Report AB). Kinematic and kinetic outcomes were used from the average of the 4 fastest balls for each pitcher. We defined overstretching as the difference in ROM between the maximal shoulder ER while pitching and ER measured by clinical evaluation (MaxERDiff) and calculated as following:

MaxERDiff = Maximal shoulder ER while pitching − ER measured in clinical evaluation.

Range of motion deficit was defined as difference in ROM between the dominant and nondominant arms within subjects. Positive values indicate that ROM of the dominant arm is greater than the nondominant arm. Participants with equal to or more than 160° of total arc ROM were classified as controls, and participants with less than 160° of total arc ROM were assigned to the lower ROM group. After allocating participants into control and lower ROM

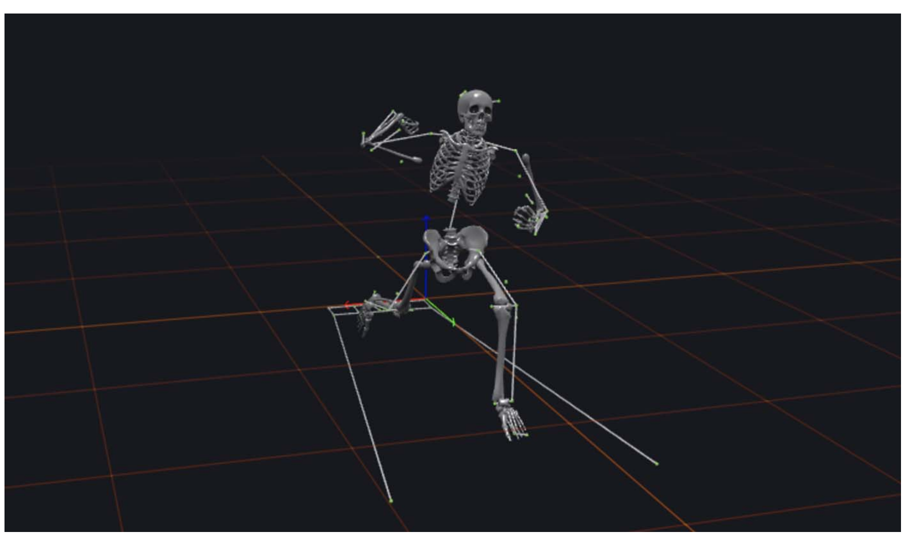

Figure 2. Skeletal model from the 3-dimensional motion capture system. The figure displays the maximal shoulder external rotation while pitching. The red arrow depicts the x axis (mediolateral), the green arrow indicates the y axis (anteroposterior), and the blue arrow depicts the z axis (vertical).

Table 1. Physical Characteristics

	Control (n = 38)	Lower ROM (n = 19)	*P* Value[a]	Range
Age, y	20.9 ± 1.6	20.1 ± 1.8	.098	18–24
Height, cm	186.0 ± 5.7	188.1 ± 6.5	.231	178–206
Mass, kg	91.1 ± 9.6	90.7 ± 10.6	.883	71.7–117.9
BMI, kg/m^2	26.3 ± 2.6	25.6 ± 2.1	.29	20.8–32.6
Dominant arm ROM (°)				
ER	114.7 ± 13.2	95.7 ± 8.5	**<.001**	80–144
IR	59.8 ± 11.4	52.6 ± 11.6	**.015**	30–89
Total arc glenohumeral ROM	174.5 ± 10.5	148.3 ± 9.0	**<.001**	129–204
Nondominant arm ROM (°)				
ER	106.9 ± 12.5	92.3 ± 11.5	**<.001**	75–133
IR	69.0 ± 12.1	68.5 ± 9.2	.862	45–95
Total arc glenohumeral ROM	175.9 ± 12.7	160.7 ± 12.4	**<.001**	140–207

Abbreviations: BMI, body mass index; ER, external rotation; IR, internal rotation; ROM, range of motion.
[a] Bold values are significant at $P < .05$.

groups, Levene's test was performed to assess the assumption of homogeneity, and independent samples *t* tests were performed using IBM SPSS statistics software (Version 28.0, IBM Inc) to compare the mean of each variable between groups. When Levene's test was significant, we further performed the Mann-Whiteney *U* test. Alpha levels were set at $P < .05$ before the data analysis and Cohen d effect sizes were calculated and interpreted as *small* (<0.3), *moderate* (0.3–0.5), and *large* (>0.5).[19]

RESULTS

Physical Characteristics

Fifty-seven baseball pitchers participated in this study. Thirty-eight participants were allocated into the control group (age = 20.9 ± 1.6 years, height = 186.0 ± 5.7 cm, and mass = 91.1 ± 9.6 kg), and 19 participants were assigned for the lower ROM group (age = 20.1 ± 1.8 years, height = 188.1 ± 6.5 cm, and mass = 90.7 ± 10.6 kg). No statistically significant difference was found in the demographics (Table 1). Only dominant ER is not normally distributed between groups ($U = 85.5$, $P < .001$), but other independent variables met the assumption of homogeneity. The lower ROM group had significantly more deficits in ER, IR, and total arc glenohumeral ROM than the control group (mean ER deficit: lower ROM = 3.5° ± 6.2°, control = 7.8° ± 9.6°, $P = .041$; IR deficit: lower ROM = −15.9° ± 14.2°, control = −9.2° ± 10.7°, $P = .027$; total arc deficit: lower ROM = −12.4° ± 13.9°, control = −1.5° ± 10.0°, $P < .001$; Table 2).

Table 2. Glenohumeral ROM Deficits (in °)[a]

	Control (n = 38)	Lower ROM (n = 19)	*P* Value[b]	Cohen *d*
Dominant ER deficit	7.8 ± 9.6	3.5 ± 6.2	**.041**	0.498
Dominant IR deficit	–9.2 ± 10.7	–15.9 ± 14.2	**.027**	0.555
Total arc ROM deficit	–1.5 ± 10.0	–12.4 ± 13.9	**<.001**	0.959

Abbreviations: ER, external rotation; IR, internal rotation; ROM, range of motion.
[a] Positive values indicate the dominant arm is greater than the nondominant arm.
[b] Bold values are significant at $P < .05$.

The control group had less overstretching in ER with the throwing shoulder. The lower ROM group had significantly less maximal ER while pitching than the control group (lower ROM = 160.1° ± 11.0°, control = 170.5° ± 13.3°, $P = .002$; Table 3). The lower ROM group also demonstrated significantly greater MaxERDiff (lower ROM = 64.4° ± 12.1°, control = 55.8° ± 16.6°, $P = .025$; Figure 3).

The control group had statistically significant faster ball velocity than the lower ROM group (control = 85.0 ± 4.3 mph, lower ROM = 82.4 ± 4.8 mph, $P = .024$; Figure 4). Additionally, the control group demonstrated significantly greater shoulder horizontal abduction at the stride phase (control = 21.0° ± 13.7°, lower ROM = 7.3° ± 14.3°, $P < .001$). No statistically significant difference was found between groups in shoulder distraction force, shoulder internal torque, elbow flexion angle, and elbow valgus torque (Table 3).

DISCUSSION

The current study investigated whether pitchers with less than 160° of total arc glenohumeral ROM had differences in stress in the throwing shoulder and elbow while pitching compared with those with 160° or greater total arc ROM. This threshold was determined based on findings from a previous meta-analysis, and we aimed to examine how pitchers with limited total arc ROM differed in their pitching biomechanics from those with optimal total arc ROM.[14] We found pitchers with 160° or greater total arc ROM exhibited less deficits in shoulder ROM and less difference in range between maximal shoulder ER while pitching and clinically measured ER. These findings confirm our hypotheses that pitchers with ideal total arc ROM present with less deficits in shoulder ROM and less difference between maximal shoulder ER while pitching and clinically measured shoulder ER in the shoulder. Contrary to our hypothesis, we did not find significant differences in shoulder and elbow kinetics. Finally, pitchers with optimal total arc ROM pitched balls faster than those with limited total arc ROM.

The lower ROM group had significantly greater total arc glenohumeral ROM deficits than the control group. As we defined deficit as the difference in ROM between dominant

Table 3. Mean Differences in Pitching Metrics

	Control (n = 38)	Lower ROM (n = 19)	*P* Value[a]	Cohen *d*
Ball velocity, mph	85.0 ± 4.3	82.4 ± 4.8	**.047**	0.571
Kinematics				
MER	170.5 ± 13.3	160.1 ± 11.0	**.002**	0.822
MaxERDiff	55.8 ± 16.6	64.4 ± 12.1	**.025**	–0.562
Elbow flexion angle at late cocking,°	92.6 ± 9.4	89.2 ± 8.0	.185	0.377
Shoulder horizontal abduction at stride	21.0 ± 13.7	7.3 ± 14.3	**<.001**	–0.99
Kinetics				
Max shoulder distraction force, BW%	140.0 ± 0.255	135.2 ± 0.234	.499	0.191
Max shoulder internal rotation torque, Nm	138.7 ± 61.2	136.4 ± 36.3	.439	0.043
Max elbow valgus torque, Nm	112.7 ± 29.9	121.4 ± 22.4	.133	–0.316

Abbreviations: BW%, body weight percentage; MaxERDiff, difference between maximal shoulder external rotation (ER) while pitching and passive ER measured by clinical evaluation; MER, maximal shoulder ER while pitching.
[a] Bold values are significant at $P < .05$.

and nondominant arms, our findings suggest that pitchers with less than 160° of total arc ROM may present with decreased ROM due to the underlying musculoskeletal tissue mechanics. Early baseball researchers postulated that glenohumeral IR deficit (GIRD) was linked to a variety of upper extremity injuries.[5,20] Recently, Wilk et al suggested a total rotational motion concept, in which pitchers with deficit in total arc ROM less than $-5°$ (calculated by dominant arm $-$ nondominant arm) had a significantly higher injury rate that resulted in missing time of playing in professional baseball players.[21] Soft tissue and osseous adaptations play a role in glenohumeral ROM. Paul et al found that humeral retrotorsion and posterior capsule thickness might be primary physical adaptations responsible for preseason IR ROM.[22] Additionally, the posterior rotator cuff is more related to acute loss of IR after pitching.[23] On the other hand, humeral retrotorsion contributes to an increase of ER and decrease of IR.[24,25] Because we summated IR and ER for total arc ROM and conducted the clinical evaluation before the pitching biomechanics evaluation, posterior capsule thickness might be the underlying cause of the loss of ROM in the lower ROM group.

The throwing shoulder typically externally rotates back between 170° and 190° of shoulder ER during the late cocking phase, which is significantly greater than clinically measured ER.[7,14] When the throwing shoulder is experiencing extreme ER, the biceps tendon plays a critical role in the protection. Due to the extreme ER creating powerful tension, the superior labrum gets pulled by the long head of the biceps posteriorly, which leads to shear stress on the superior labrum (a potential mechanism for SLAP tears).[2,26,27] We observed the lower ROM group demonstrate a greater difference in motion between maximal shoulder ER while pitching and clinically measured ER. Pitchers with limited total arc ROM may undergo more tension on the long biceps tendon and peel-back stress.[5] Although it may be necessary to consider thoracic extension and scapulothoracic movement, the discrepancy indicates higher risk of shoulder injury.[2]

The results also align with findings that limited total arc glenohumeral ROM is more susceptible to upper extremity injuries. Wilk et al reported that professional baseball pitchers with deficits of less than $-5°$ in total arc ROM in their dominant shoulders had a 2.6 times greater risk of shoulder injuries and surgery.[15] Our control group exhibited with $-1.5° \pm 10.0°$, whereas the risk group had $-12.4° \pm 13.9°$. As Wilk et al suggested pitchers with deficit in $-5°$ of total arc ROM as a risk indicator, pitchers with less than 160° may tend to display greater deficits. Regarding

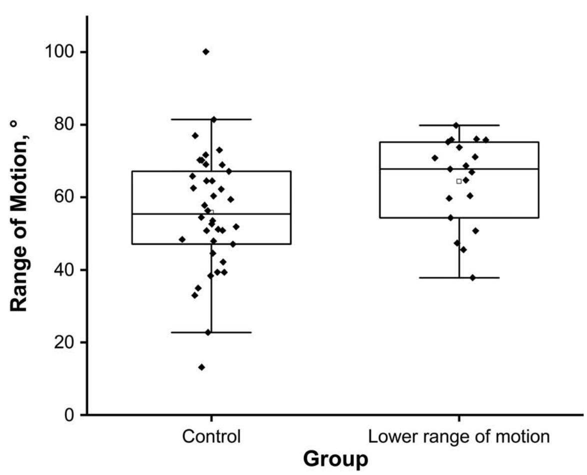

Figure 3. Comparison between groups of the mean end range between maximal shoulder external rotation while pitching and clinically measured external rotation.

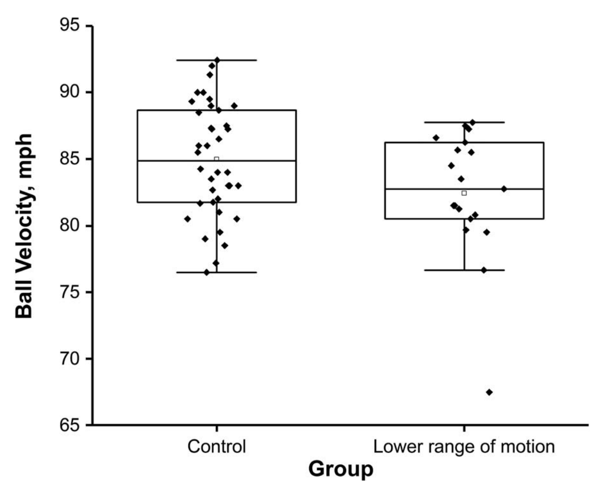

Figure 4. Comparison of mean ball velocity between groups.

shoulder ER, a statistically significant difference was found in ER between groups (control: 114.7 ± 13.2, lower ROM: 95.7 ± 8.5, $P < .001$). Professional baseball players with insufficient ER were 2.2 times more likely to suffer from a shoulder injury and 4.0 times more likely to require shoulder surgery than pitchers with optimal shoulder ER.[12] Additionally, authors of a prospective study demonstrated that, if the pitcher's throwing arm does not have 5° or greater ER than the nonthrowing arm, it could be an injury risk factor.[13] In our study, the lower ROM group falls into the suboptimal range (3.5° ± 6.2°), whereas the control group had greater than 5° difference between dominant and nondominant arms (7.8° ± 9.6°).

Regarding elbow loading, we observed 7.2% increased elbow valgus torque for the lower ROM group compared with the control group, yet the mean difference was not statistically significant ($P = .133$). Noonan et al reported that pitchers who suffered from shoulder injury sustained less humeral retrotorsion, whereas pitchers who injured their throwing elbow displayed increased humeral retrotorsion.[28] In another study, less humeral retrotorsion inversely correlated with more severe upper extremity injuries.[29] The measurement of humoral retrotorsion is not clinically accessible for everyone due to the need for training and a device such as a diagnostic ultrasound. Although traditional goniometric ROM measures may detect these changes, we did not directly measure the osseus adaptation. Thus, this may be a limitation of this study, and future researchers may want to consider direct measures of humeral torsion which may reveal the further effects of total arc ROM on medial elbow stress.

Interestingly, pitchers with greater total arc glenohumeral ROM demonstrated significantly faster ball velocity than the lower ROM group. Additionally, the control group had significantly greater horizontal abduction at the stride phase than lower ROM group. Both maximal shoulder ER at the late cocking and horizontal abduction at the stride phases are positively correlated with ball velocity, and 16° to 21° of the horizontal abduction is a typical range.[7,16] Although the interaction between glenohumeral ROM and horizontal abduction is not well understood, our finding implies that limited total arc ROM may affect pitching mechanics and performance. Thus, further research is needed to understand how glenohumeral ROM affects other anatomical planes during the pitching motion besides sagittal plane.

This study has several limitations that we must acknowledge. Our sample size with a 1:2 ratio (38 participants in the control group and 19 participants in the risk group) lacked the statistical power to determine differences in kinetic variables. Nevertheless, we observed differences in glenohumeral characteristics, shoulder kinematics while pitching, and ball velocity. Secondly, participation occurred anytime throughout the period of data collection. Thus, we did not consider timing of season in our cross-sectional study. Glenohumeral ROM is known to adapt repetitive stress from throwing, so it may be ideal to conduct this type of study with all participants before or after the official baseball season. Still, 160° can be considered a threshold to monitor degradation or progression of the ROM because pitchers may demonstrate more than 160° but display with less than 160° due to adaptation according to the amount of pitching load.

CONCLUSIONS

Pitchers with less than 160° of total arc glenohumeral ROM may undergo overstretching toward ER in the shoulder during the late cocking phase. Pitchers with greater levels of total arc ROM can pitch at the same or faster ball speed without increasing loading in the upper extremity. While it is paramount to pay attention to ER and IR individually, athletic trainers can also combine both measurements to reveal total arc glenohumeral ROM. Monitoring total arc ROM may help identify pitchers who are at higher risk of shoulder injuries, initiate preventive exercises or therapeutic interventions, and monitor arm health over time. Future researchers should consider the timing of evaluation, other clinical characteristics, such as shoulder strength and lower extremity, bony anatomical changes, and pitching habits, including pitch counts per game and rest between games in conjunction with examination of glenohumeral ROM.

REFERENCES

1. Calabrese GJ. Pitching mechanics, revisited. *Int J Sports Phys Ther*. 2013;8(5):652–660.
2. Oyama S. Baseball pitching kinematics, joint loads, and injury prevention. *J Sport Health Sci*. 2012;1(2):80–91. doi:10.1016/j.jshs.2012.06.004
3. Anz AW, Bushnell BD, Passmore Griffin L, Noonan TJ, Torry MR, Hawkins RJ. Correlation of torque and elbow injury in professional baseball pitchers. *Am J Sports Med*. 2010;38(7):1368–1374. doi:10.1177/0363546510363402
4. Walch G, Boileau P, Noel E, Donell ST. Impingement of the deep surface of the supraspinatus tendon on the posterior superior glenoid rim: an arthroscopic study. *J Shoulder Elbow Surg*. 1992;1(5):238–245. doi:10.1016/S1058-2746(09)80065-7
5. Burkhart SS, Morgan CD, Kibler WB. The disabled throwing shoulder: spectrum of pathology part I: pathoanatomy and biomechanics. *Arthroscopy*. 2003;19(4):404–420. doi:10.1053/jars.2003.50128
6. Pradhan RL, Itoi E, Hatakeyama Y, Urayama M, Sato K. Superior labral strain during the throwing motion: a cadaveric study. *Am J Sports Med*. 2001;29(4):488–492. doi:10.1177/03635465010290041801
7. Fleisig GS, Barrentine SW, Zheng N, Escamilla RF, Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. *J Biomech*. 1999;32(12):1371–1375. doi:10.1016/s0021-9290(99)00127-x
8. Werner SL, Fleisig GS, Dillman CJ, Andrews JR. Biomechanics of the elbow during baseball pitching. *J Orthop Sports Phys Ther*. 1993;17(6):274–278. doi:10.2519/jospt.1993.17.6.274
9. Nicholson KF, Hulburt TC, Beck EC, Waterman BR, Bullock GS. The relationship between pitch velocity and shoulder distraction force and elbow valgus torque in collegiate and high school pitchers. *J Shoulder Elbow Surg*. 2020;29(12):2661–2667. doi:10.1016/j.jse.2020.04.046
10. Manzi J, Kew M, Zeitlin J, et al. Increased pitch velocity is associated with throwing arm kinetics, injury risk, and ulnar collateral ligament reconstruction in adolescent, collegiate, and professional baseball pitchers: a qualitative systematic review. *Arthroscopy*. 2023;39(5):1330–1344. doi:10.1016/j.arthro.2023.01.004
11. Wilk KE, Macrina LC, Fleisig GS, et al. Deficits in glenohumeral passive range of motion increase risk of elbow injury in professional baseball pitchers: a prospective study. *Am J Sports Med*. 2014;42(9):2075–2081. doi:10.1177/0363546514538391
12. Wilk KE, Macrina LC, Fleisig GS, et al. Deficits in glenohumeral passive range of motion increase risk of shoulder injury in professional baseball pitchers: a prospective study. *Am J Sports Med*. 2015;43(10):2379–2385. doi:10.1177/0363546515594380

13. Camp CL, Zajac JM, Pearson DB, et al. Decreased shoulder external rotation and flexion are greater predictors of injury than internal rotation deficits: analysis of 132 pitcher-seasons in professional baseball. *Arthroscopy*. 2017;33(9):1629–1636. doi:10.1016/j.arthro.2017.03.025
14. Bullock GS, Faherty MS, Ledbetter L, Thigpen CA, Sell TC. Shoulder range of motion and baseball arm injuries: a systematic review and meta-analysis. *J Athl Train*. 2018;53(12):1190–1199. doi:10.4085/1062-6050-439-17
15. Reinold MM, Gill TJ, Wilk KE, Andrews JR. Current concepts in the evaluation and treatment of the shoulder in overhead throwing athletes, part 2: injury prevention and treatment. *Sports Health*. 2010;2(2):101–115. doi:10.1177/1941738110362518
16. Escamilla RF, Barrentine SW, Fleisig GS, et al. Pitching biomechanics as a pitcher approaches muscular fatigue during a simulated baseball game. *Am J Sports Med*. 2007;35(1):23–33. doi:10.1177/0363546506293025
17. Wilk KE, Reinold MM, Macrina LC, et al. Glenohumeral internal rotation measurements differ depending on stabilization techniques. *Sports Health*. 2009;1(2):131–136. doi:10.1177/1941738108331201
18. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech*. 2007;23(1):42–51. doi:10.1123/jab.23.1.42
19. Cohen J. A power primer. *Psychol Bull*. 1992;112(1):155–159. doi:10.1037//0033-2909.112.1.155
20. Dines JS, Frank JB, Akerman M, Yocum LA. Glenohumeral internal rotation deficits in baseball players with ulnar collateral ligament insufficiency. *Am J Sports Med*. 2009;37(3):566–570. doi:10.1177/0363546508326712
21. Wilk KE, Macrina LC, Fleisig GS, et al. Correlation of glenohumeral internal rotation deficit and total rotational motion to shoulder injuries in professional baseball pitchers. *Am J Sports Med*. 2011;39(2):329–335. doi:10.1177/0363546510384223
22. Paul RW, Erickson BJ, Cohen SB, et al. Identifying the underlying mechanisms responsible for glenohumeral internal rotation in professional baseball pitchers. *J Shoulder Elbow Surg*. 2022;7(1):138–142. doi:10.1016/j.jseint.2022.09.005
23. Mirabito NS, Topley M, Thomas SJ. Acute effect of pitching on range of motion, strength, and muscle architecture. *Am J Sports Med*. 2022;50(5):1382–1388. doi:10.1177/03635465221083325
24. Crockett HC, Gross LB, Wilk KE, et al. Osseous adaptation and range of motion at the glenohumeral joint in professional baseball pitchers. *Am J Sports Med*. 2002;30(1):20–26. doi:10.1177/03635465020300011701
25. Myers JB, Laudner KG, Pasquale MR, Bradley JP, Lephart SM. Glenohumeral range of motion deficits and posterior shoulder tightness in throwers with pathologic internal impingement. *Am J Sports Med*. 2006;34(3):385–391. doi:10.1177/0363546505281804
26. Kuhn JE, Lindholm SR, Huston LJ, Soslowsky LJ, Blasier RB. Failure of the biceps superior labral complex: a cadaveric biomechanical investigation comparing the late cocking and early deceleration positions of throwing. *Arthroscopy*. 2003;19(4):373–379. doi:10.1053/jars.2003.50044
27. Burkhart SS, Morgan CD. The peel-back mechanism: its role in producing and extending posterior type II SLAP lesions and its effect on SLAP repair rehabilitation. *Arthroscopy*. 1998;14(6):637–640. doi:10.1016/s0749-8063(98)70065-9
28. Noonan TJ, Thigpen CA, Bailey LB, et al. Humeral torsion as a risk factor for shoulder and elbow injury in professional baseball pitchers. *Am J Sports Med*. 2016;44(9):2214–2219. doi:10.1177/0363546516648438
29. Polster JM, Bullen J, Obuchowski NA, Bryan JA, Soloff L, Schickendantz MS. Relationship between humeral torsion and injury in professional baseball pitchers. *Am J Sports Med*. 2013;41(9):2015–2021. doi:10.1177/0363546513493249

Address correspondence to Tomohiro Ide, MA, ATC, School of Health and Kinesiology, University of Nebraska at Omaha, 6001 Dodge Street, Omaha, NE 68182. Address email to tide@unomaha.edu.