


Original Research

Does High Medial Elbow Stress During Pitching Compromise the Dynamic Stabilizers of The Elbow?

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Background

The flexor carpi ulnaris (FCU) and flexor digitorum superficialis (FDS) are thought to provide dynamic stability to the medial elbow, with a lesser contribution from the pronator teres (PT).

Hypothesis/Purpose

The purpose of this study was to determine if baseball pitchers with higher valgus elbow torque experience greater FCU and FDS strength loss.

Study Design

Controlled Laboratory Study

Methods

A pilot study was performed to determine if middle and ring finger flexion strength tests preferentially activated the FCU and FDS versus the PT (10 men age 36±12 yr). EMG amplitudes, expressed as percent of maximal voluntary contraction (MVC) were compared between tests and muscles. In a field study of college baseball pitchers, middle finger, ring finger and grip strength were tested prior to, immediately after, and one day after 14 pitching performances in 10 pitchers (21±2 yr). Elbow valgus torque was measured from an inertial measurement unit, housed in a compression sleeve and pitchers were categorized as having high or low valgus torque.

Results

For the pilot study EMG activations were 74% FDS, 66% FCU and 35% PT for the middle finger test (muscle effect $p=0.032$) and 93% FCU, 61% FDS and 23% PT for the ring finger test (muscle effect $p=0.005$). In the field study, pitchers with high valgus torque showed marked post-game middle finger fatigue (88% of baseline) and incomplete recovery the following day (95%), while pitchers with low valgus torque showed no strength loss (107% post game, 106% a day later; group x time $p=0.022$). Results were similar for ring finger strength (high torque: 94% post game 96% a day later; low torque: 114% post game 107% a day later; group x time $p=0.048$). By contrast, grip strength was not different between pitchers with high versus low valgus torque ($p=0.143$).

Conclusion

High medial elbow stress during pitching fatigues the dynamic stabilizers of the medial elbow.

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Level of Evidence

Level 3

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INTRODUCTION

Elbow injuries in general, and ulnar collateral ligament (UCL) injuries in particular, have become an increasing problem in baseball.¹ Over the last 25 years the predominant injury in major league baseball (MLB) has shifted from the shoulder to the elbow.¹ The vast majority of UCL injuries are seen in pitchers at both the professional and collegiate level.²

The muscles of the flexor pronator mass can provide dynamic stability to the medial elbow.⁵⁻⁷ Specifically, the flexor carpi ulnaris (FCU) and the flexor digitorum superficialis (FDS) have been shown to provide dynamic stability, with a lesser contribution from the pronator teres (PT).^{3, 6, 7} In line with these findings,^{3, 6, 7} exercise-induced wrist flexion fatigue has been shown to increase medial elbow gapping under valgus stress.⁵ The FDS and FCU are highly active during the acceleration and deceleration phases of the pitching motion⁸ (FDS 80%-71% MVC, FCU 112%-77% MVC) and likely provide dynamic elbow stability. In support of this, FCU and FDS elasticity have been shown to increase after repeated pitches and the change was correlated with an increase in medial elbow joint space.⁹

In response to the increased prevalence of elbow injuries in baseball there has been increased interest in measuring the stress in the medial elbow during pitching. To this end, a wearable inertial sensor has been developed to quantify medial elbow torque during pitching.^{10, 11} Medial elbow valgus torque, an index of valgus stress on the elbow, was shown to be higher for fastballs and changeups compared with curveballs.¹¹ Additionally, valgus torque increased in later innings of a simulated game, despite a decline in pitch velocity, and this effect was attributed to fatigue.¹¹ However, the association between valgus torque at the elbow during pitching and muscle fatigue in the dynamic stabilizers of the elbow has not been previously examined. It is possible that pitchers with high valgus torque during pitching experience greater fatigue in the dynamic stabilizers of the elbow and thus are at increased risk of injury.

The first step in studying a possible relationship between high valgus elbow torque during pitching and excessive fatigue in the dynamic stabilizers of the elbow is to develop a strength test for the dynamic stabilizers. Previous work in college pitchers has shown that grip strength is minimally impaired post game¹² or the next day.¹³ It remains unclear whether grip strength is a good indicator of fatigue in the stabilizers of the medial elbow. Developing a strength test specific to the FCU and FDS could provide important information on dynamic stability of the medial elbow in pitchers. Middle finger extension strength measured with a hand-held dynamometer has been shown to provide a good measure of impairment in patients with lateral elbow tendinopathy.¹⁴ Applying the same methodology to finger flexion strength might provide an indicator of medial elbow function.

Therefore, the purposes of this study were twofold: (1) initially determine if finger flexion strength testing with a hand-held dynamometer selectively activates the FCU and FDS, (2) determine if baseball pitchers with higher valgus elbow torque experience greater FCU and FDS strength loss. It was hypothesized (1) that the FCU and FDS would be preferentially activated during middle and ring finger flexion MVC testing, and (2) that pitchers with higher elbow valgus torque would experience greater finger flexion fatigue and slower recovery.

MATERIALS AND METHODS

This study was divided into two sections: (1) a pilot study in healthy control subjects to develop FCU and FDS strength tests and (2) a field study in college baseball pitchers to examine fatigue in the FCU, FDS and grip tests and the relationship to valgus elbow torque during pitching. The pilot study and the field study were approved by institutional review board and all participants gave written informed consent.

PILOT STUDY: DEVELOPMENT OF FCU AND FDS STRENGTH TESTS

Electromyograms (EMG) were recorded from the FCU, FDS and PT during manual muscle testing of middle finger and ring finger flexion strength on the dominant side in 10 healthy men (age 36±12 yr) using a 16-channel BTS FREEMG 300 system, CMRR: >110 dB at 50–60 Hz; input impedance: >10 GΩ (BTS Bioengineering, Milan, Italy). After the skin of each participant was shaved, cleaned, and lightly abraded, disposable silver/silver chloride passive dual electrodes (2.0-cm interelectrode distance) (Noraxon, Scottsdale, AZ) were applied. Electrodes were placed over muscle belly at the proximal medial forearm (FCU),¹⁵ one quarter the distance from medial humeral epicondyle to the skin fold at the wrist (FDS)¹⁶ and diagonally over muscle belly, slightly distal to skin fold in cubital fossa (PT).¹⁵ Maximum voluntary contraction (MVC) tests were performed for each muscle: maximal resisted wrist flexion and ulnar deviation for FCU testing; maximal resisted four-finger flexion with opposition applied across the middle phalanges for FDS testing; and maximal resisted forearm pronation with slight elbow flexion for PT.¹⁷ Since these MVC tests are not conducive to testing with a hand-held dynamometer for quantifying strength, the middle finger and ring finger flexion tests were chosen for strength testing.

For both the pilot study and field study finger flexion strength was performed with a hand-held dynamometer (Lafayette Instruments, Lafayette, IN). Subjects were seated for testing with the elbow flexed approximately 40°, with the forearm supinated and rested on a flat surface with the wrist in neutral position ([Figure 1](#)). The subject stabi-

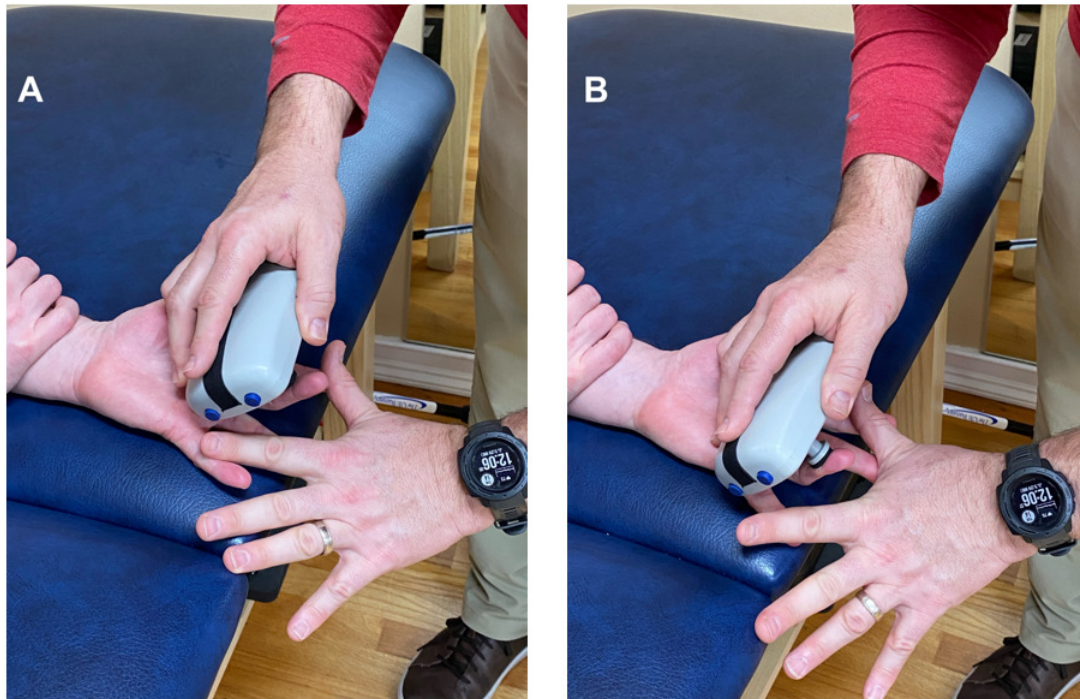


Figure 1. (A) Middle finger flexion strength test. (B) Ring finger flexion strength test. The dynamometer was placed just proximal to the distal interphalangeal joint.

lized their forearm with their contralateral hand, pressing it firmly against the table while avoiding the surface electrodes. The subject then flexed the test finger (middle or ring finger) while the tester stabilized the other three fingers against the table. Then the tester placed the 1 cm diameter probe of the dynamometer distally on the middle phalanx just proximal to the distal interphalangeal joint. The subject maximally flexed the test finger against the dynamometer while the tester extended the finger (break test). Two trials were performed for each test. A third trial was performed if there was a marked difference between the first two trials (>30%) and subsequently the outlier was discarded and the mean of two was recorded. Index finger flexion break test strength has previously been shown to be reliable.¹⁸ Additionally, a hand-held dynamometer test set up has previously been used to detect middle finger extension weakness and treatment training effects in patients with lateral epicondylitis.¹⁴

PILOT STUDY STATISTICS

Middle versus ring finger strength were compared using a paired t test. Differences in FCU, FDS and PT activation between the middle and ring fingers were compared using Test (middle versus ring finger) by Muscle (FCU, FDS, PT) repeated measures analysis of variance. The dependent variable was EMG expressed as a percentage of MVC. Pair-wise comparisons between tests and between fingers were made using the least significant difference approach.

FIELD STUDY IN PITCHERS

PROCEDURES

Middle and ring finger flexion strength and grip strength were measured immediately prior to a game, immediately after the pitcher was removed from the game, and on the day after the game. The study participants were 10 NCAA division 3 baseball pitchers (3 freshmen, 1 sophomore, 2 juniors, 4 seniors; age 21 ± 2 yr, height 1.83 ± 0.06 m, body mass 85.4 ± 9.2 kg). Data were collected during intra-squad scrimmages and preseason games in the Fall season, with 6 pitchers having data from one performance and 4 pitchers having data from two performances (total 14 game data sets). Elbow valgus torque was measured from an inertial measurement unit (Motus Global, Massapequa, NY), housed in a compression sleeve, worn on the elbow during pregame bullpen pitches. The inertial measurement unit was removed prior to the game (the pitchers preferred not to wear the device). The elbow valgus torque from the bullpen pitches was averaged for each pitcher. Pitch velocities were not measured for the games used in this study. However, each player had his fast ball velocity measured earlier in the season which was used during analysis. All participants gave written informed consent, and the study was approved by institutional review board.

Middle and ring finger flexion strength were measured as described in the methods for the pilot study. Grip strength measurements were taken in a standing position using a hydraulic hand dynamometer (Jamar; Performance Health, Warrenville, IL). Pitchers were instructed to have their shoulder adducted and neutrally rotated, elbow flexed at 90° , and forearm in neutral position during the grip test.

Table 1. Muscle activation (%MVC) during middle and ring finger flexion strength tests (mean±SD)

	MIDDLE FINGER	RING FINGER
FCU	66±44%	93±64%
FDS	74±25%	61±31%
PT	35±22%	23±13%

FCU, flexor carpi ulnaris; FDS, flexor digitorum superficialis; PT, pronator teres. Muscle Effect $p=0.008$; Test Effect $p=0.874$; Muscle by Test $p=0.01$. Middle Finger muscle effect $p=0.032$; FDS>PT $p=0.005$. Ring Finger muscle effect $p=0.005$; FCU>PT $p=0.010$; FDS>PT $p=0.002$.

Pitchers were instructed to squeeze the dynamometer as hard as they could (isometric test). The average of two trials was recorded and used for data analysis.

The inertial measurement unit was aligned with the medial aspect of the ulna approximately 5 cm distal to the medial epicondyle of the humerus and held in place with a commercial sleeve. In addition to elbow torque (peak elbow valgus torque) the sensor calculates arm slot angle (angle of forearm relative to the ground at ball release), arm speed (peak forearm angular velocity in degrees per second) and shoulder rotation angle (angle between forearm and ground at maximum external rotation). Pitchers were classified as high elbow valgus torque (above the mean for the group) or low elbow valgus torque (below mean for the group).

FIELD STUDY STATISTICS

Pitchers were categorized as having high or low valgus torque (see results section for details). Effect of valgus elbow torque on fatigue and strength recovery was assessed using mixed-model ANOVA. Based on the pilot study, it was estimated that with 14 pitching performances there would be 80% power to detect a 11% change in middle finger strength after a pitching performance ($p<0.05$). Pearson correlation coefficients and stepwise multiple regression were used to identify factors associated with post game fatigue.

RESULTS

PILOT STUDY

Finger flexion force was significantly greater for the middle finger test versus the ring finger test (75 ± 17 N vs. 52 ± 9 N, $P<0.001$). Muscle activations varied significantly between muscles and between tests (Table 1). FDS activity was greater than PT activity for both the middle finger test ($p=0.005$) and the ring finger test ($p=0.002$). FCU activity was higher than PT activity for the ring finger test (0.010). Therefore, the finger flexion tests preferentially activated the FDS and FCU over the PT.

FIELD STUDY

The pitchers threw 58 ± 13 pitches in the 14 games (range 42 to 82 pitches) not including bullpen warm up throws. For the bullpen pitches valgus elbow torque was 50.7 ± 14.3 Nm with an arm slot angle of $48\pm 9^\circ$, an arm speed of $912\pm 116^\circ/s$

and a shoulder rotation angle of $145\pm 10^\circ$. The number of bullpen pitches varied between pitchers (range 20-29), but elbow valgus torque for a given pitcher did not vary markedly between pitches, with an average coefficient of variation of 14%. Elbow torque values were very similar between games for the four pitchers with data from two games, varying by 6.6%, 9.3%, 0.2%, and 5.4% (Figure 2).

Four pitchers (6 games) had elbow torques below 50 Nm (35.9 ± 3.2 Nm, range 30.9-40.2 Nm). Six pitchers (8 games) had elbow torques above 50 Nm (61.7 ± 6.5 Nm, range 52.5-68.8 Nm). The total number of game pitches was not different between the low and high elbow valgus torque groups (53 ± 11 vs 61 ± 13 , $p=0.263$). The high torque group comprised pitchers with higher ($p=0.010$) pitch velocity (87 ± 2 mph) than the pitchers in the low torque group (82 ± 2 mph).

Pregame strength was 77.1 ± 11.3 N for middle finger flexion, 58.5 ± 11.2 N for ring finger flexion and 552 ± 76 N for grip strength. Middle and ring finger flexion fatigue, and subsequent recovery, were worse for pitchers with high valgus elbow torque compared with pitchers with low valgus elbow torque (Group by Time $p=0.022$ middle finger, Figure 3, $p=0.031$ ring finger, Figure 4). Pitchers with high torque had greater post-game fatigue than pitchers with low torque for middle finger flexion ($88\pm 10\%$ of baseline strength vs. $107\pm 18\%$, $p=0.026$) and ring finger flexion (94 ± 13 vs. $114\pm 13\%$, $p=0.016$). By contrast, changes in grip strength were unaffected by elbow torque (Group by Time $p=0.143$, Figure 5).

Post-game middle finger flexion fatigue was correlated with the number of pitches thrown ($r=0.617$, $p=0.019$) and elbow valgus torque ($r=0.597$, $p=0.024$). The combination of pitch count and elbow valgus torque explained 57% of the variance in middle finger flexion fatigue ($R=0.755$, $p=0.010$). Post-game ring finger flexion fatigue was correlated with the number of pitches thrown ($r=0.552$, $p=0.041$) and elbow valgus torque ($r=0.632$, $p=0.015$). The combination of pitch count and elbow valgus torque did not further improve the prediction of ring finger fatigue. Neither pitch count ($r=0.058$, $p=0.845$) nor elbow torque ($r=0.426$, $p=0.129$) were correlated with grip fatigue.

DISCUSSION

In the pilot study the EMG data from the FCU, FDS and PT indicated that middle and ring finger flexion tests activated the FCU and FDS substantially more than the PT. Previous literature showed that the FCU and FDS provide dynamic stability to the medial elbow.³⁻⁷ In the field study pitchers with greater elbow valgus stress during pitching experienced greater fatigue in the finger flexion tests. This indicates that pitchers with high valgus elbow stress place greater demand on the dynamic stabilizers and thus exhibit greater fatigue in these muscles. By contrast, change in grip strength, which is a more general test of forearm fatigue, was unaffected by elbow valgus stress.

It was anticipated that the middle and ring finger flexion tests would activate the FDS since the MVC test for the FDS is resisted four finger flexion. A hand-held dynamometer

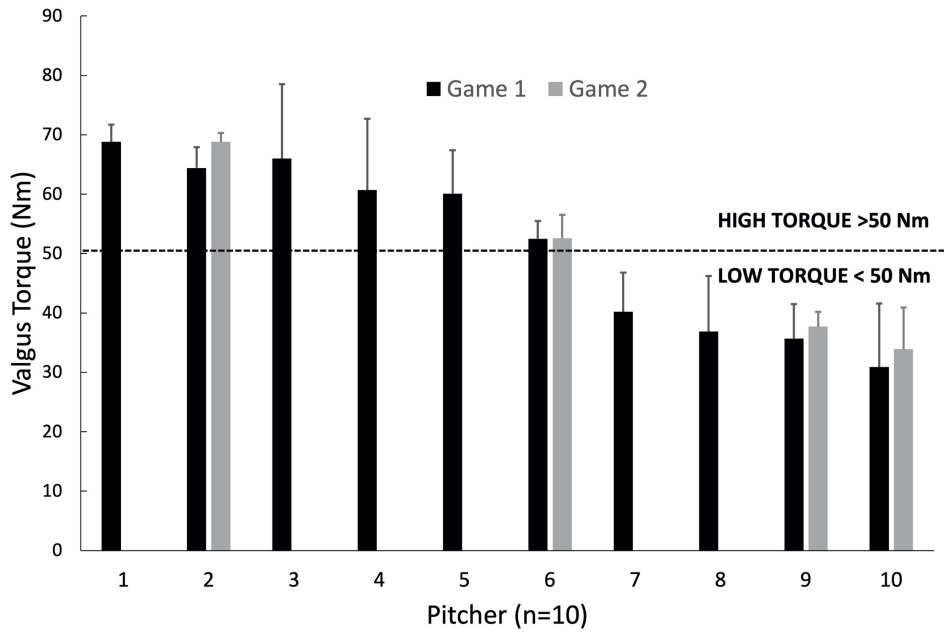


Figure 2. Elbow valgus torque for the 10 pitchers. Players were classified as high (n=6) or low (n=4) valgus torque pitchers. Mean±SD displayed.

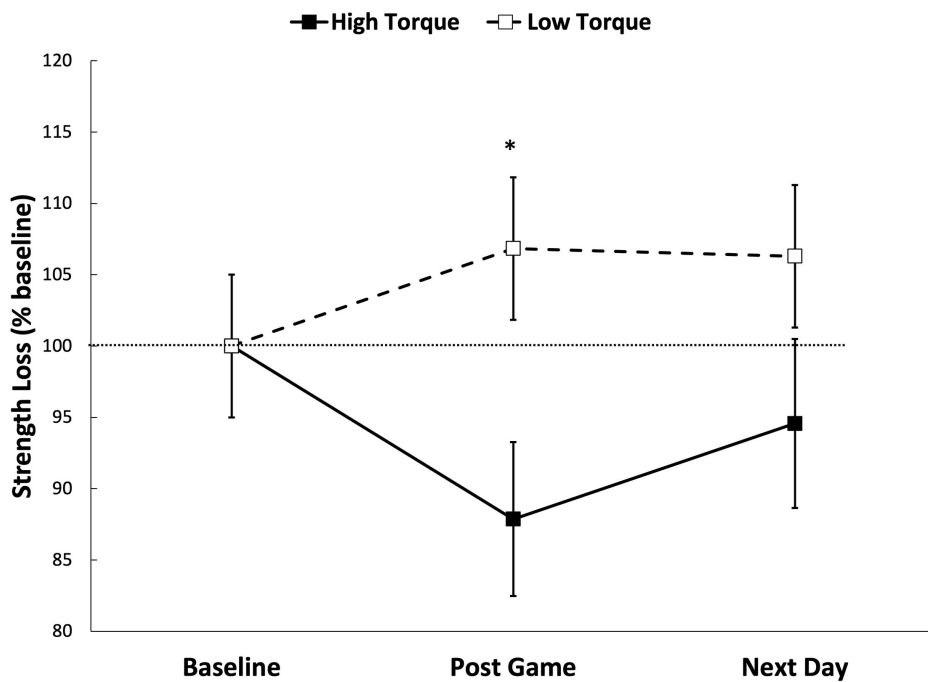


Figure 3. Middle finger flexion strength immediately post game and one day later. Effect of Time p=0.587, Effect of Elbow Torque p=0.048, Torque by Time p=0.022. * Significant difference between low and high torque groups (p<0.05). Mean±SE are displayed.

test of four finger flexion was not attempted because there would be no way to uniformly apply resistance across the four fingers to allow comparable contributions from each finger. Since the FCU tendon inserts on the pisiform and is not attached to the carpal bones, it is surprising that it was so highly active during ring finger flexion. This may

reflect synergistic action between finger and wrist flexion and the role of the pisiform. In fact, ring finger flexion has been shown to contribute to medial stability of the elbow.¹⁹ However, both middle finger flexion and index finger flexion have been shown to provide greater medial stability that

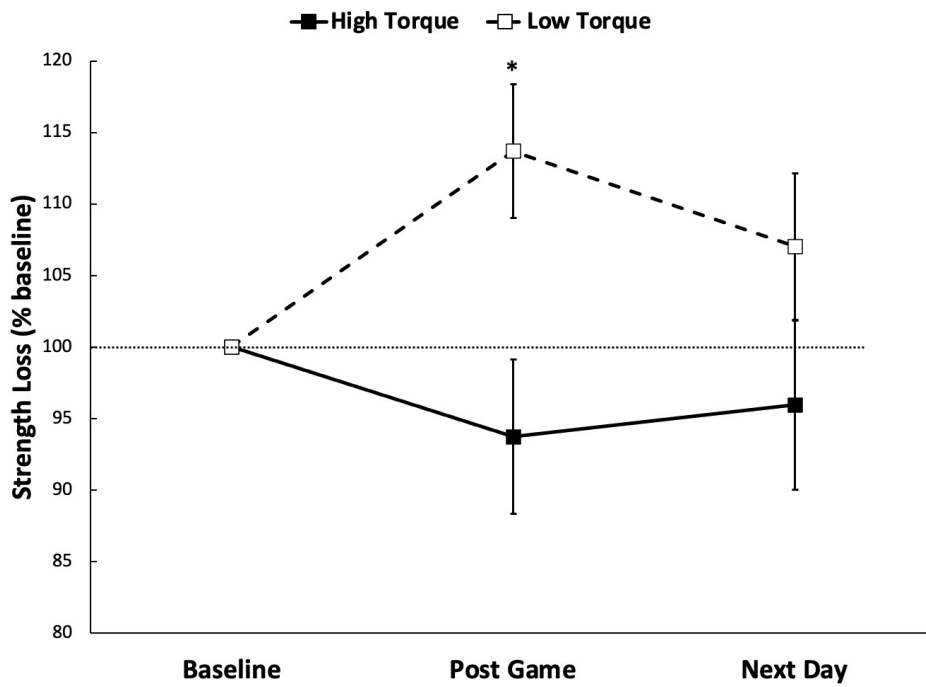


Figure 4. Ring finger flexion strength immediately post game and one day later. Effect of Time $p=0.624$, Effect of Elbow Torque $p=0.048$, Torque by Time $p=0.031$. * Significant difference between low and high torque groups ($p<0.05$). Mean \pm SE are displayed.

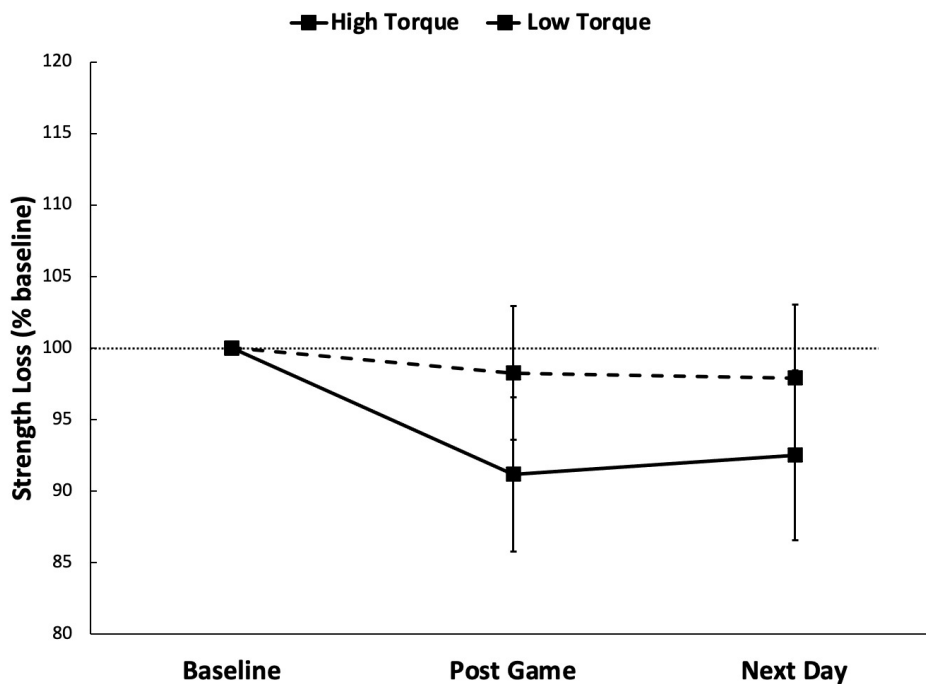


Figure 5. Grip strength immediately post game and one day later. Effect of Time $p=0.013$, Effect of Elbow Torque $p=0.077$, Torque by Time $p=0.143$. Mean \pm SE are displayed.

the ring finger.¹⁹ Future work should examine index finger strength changes in baseball pitchers.

While the focus of this study was middle and ring finger flexion strength in relation to medial elbow stability, previous work has shown that full grip contraction (mass grasp) can stabilize the medial elbow.²⁰ However, changes in grip

strength in the present study were not associated with the valgus torque on the medial elbow during pitching. Therefore, these results support finger flexion strengthening exercises for baseball pitchers as opposed to grip strengthening exercises. Similarly, others have proposed that index

and middle finger flexion exercises be added to throwers' injury prevention training programs.¹⁹

Higher pitch velocities are associated with greater valgus torque at the elbow, however, this relationship is more pronounced within pitchers than between pitchers.²¹ Pitch velocity explained 96% of the variance in elbow torque when looking at individual professional pitchers throwing at a range of different velocities.²¹ By contrast, pitch velocity only explained 8% of the variability in elbow torque when comparing data across a group of professional pitchers.²¹ Thus, variation in individual pitchers' stature, anthropometrics and biomechanics likely contribute markedly to the elbow torque.

The wearable inertial sensor used in this study can provide useful information for monitoring and managing pitchers. Part of the rationale for the study was the finding that valgus elbow torque measured with this sensor increased progressively after three innings of a simulated game despite a decline in pitch velocity.¹¹ This increased medial elbow stress was attributed to fatigue, but the only measure of fatigue was a visual analog scale used to capture the pitcher's perception of fatigue with each inning pitched. There was clear heterogeneity in valgus elbow torque between the pitchers studied here, and homogeneity between games for pitchers with data from two games. Given the individual nature of valgus torque profiles in pitchers^{10,11} a prospective study of valgus elbow torque and injury risk across a large sample of pitchers is warranted.

One limitation was the relatively small number of pitches (58±13) thrown by the pitchers in this study. Because the games were intrasquad scrimmages and pre-season games, pitchers were scheduled to pitch a set number of innings in each game. Most pitchers were restricted to four innings thus limiting the total number of pitches. Middle and ring finger fatigue were correlated with pitch count. For the middle finger, pitch count and elbow torque combined to explain 57% of the variance in fatigue. For the ring finger elbow torque explain 40% of the variance in fatigue and pitch count explained 30%, but the combination did not further explain the variance.

While the sample size was sufficient to demonstrate an effect of elbow valgus torque on finger flexion fatigue the data should be viewed as preliminary. Data on a greater number of pitchers throwing a greater number of pitches is needed to fully understand the role of elbow valgus torque in fatigue of the dynamic stabilizers of the medial elbow. Additionally, the sample size was insufficient to fully examine recovery of finger flexion strength on the day after the game. The data were equivocal with regards to the role of elbow torque and the extent of recovery.

Ideally pitch velocity would have been measured in the games studied here (instead of at an independent time during the season) since higher velocities are associated with greater elbow valgus torque.²¹ However, the relationship between fastball velocity and elbow torque was not

strong in professional pitchers.²¹ Furthermore, weighted-ball throwing training was sufficient to increase pitch velocity with no change in elbow torque.²² It remains to be determined whether high elbow valgus torque independent of pitch velocity leads to earlier fatigue of the dynamic stabilizers of the medial elbow. If so, identifying high velocity pitchers that pitch with low valgus elbow torque may be beneficial.

It would have been preferable if the EMG measurements to validate the tests of FCU and FDS function were performed on the baseball pitchers. However, this would have involved significantly more time with the pitchers, who were in season at the time of data collection. The team did not provide additional time to conduct EMG testing on the players. Using a healthy control group in a laboratory setting provided a greater degree of control than would have been possible with the pitchers and was able to confirm the recruitment of key muscles during various tests.

While the results of this study point to the potential utility of finger flexion strength measures in baseball pitchers it is important to establish the reliability of this measure and the degree of tester expertise required to obtain reliable measures. The tester in this study had more than 20 years of experience using this hand-held dynamometer to test baseball pitchers. Had there been substantial measurement variability it would not have been possible to detect the effects of elbow valgus torque on finger flexion strength. However, since this is not a widely used strength test it remains to be seen how useful the measurement is in the hands of other clinicians.

CONCLUSION

The results of this study indicate that pitchers with higher valgus elbow torque during pitching experience greater fatigue in the dynamic stabilizers of the medial elbow. This may lead to excessive stress on the UCL. These pitchers may benefit from finger flexion strength training to maintain dynamic stability of the medial elbow during a pitching performance.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to report.

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REFERENCES

1. Conte S, Camp CL, Dines JS. Injury trends in Major League Baseball over 18 seasons: 1998-2015. *Am J Orthop*. 2016;45:116-123.
2. Rothermich MA, Conte SA, Aune KT, Fleisig GS, Cain ELJ, Dugas JR. Incidence of elbow ulnar collateral ligament surgery in collegiate baseball players. *Orthop J Sports Med*. 2018;6(4):232596711876465. doi:10.1177/2325967118764657
3. Davidson PA, Pink M, Perry J, Jobe FW. Functional anatomy of the flexor pronator muscle group in relation to the medial collateral ligament of the elbow. *Am J Sports Med*. 1995;23(2):245-250. doi:10.1177/036354659502300220
4. Frangiamore SJ, Bigart K, Nagle T, Colbrunn R, Millis A, Schickendantz MS. Biomechanical analysis of elbow medial ulnar collateral ligament tear location and its effect on rotational stability. *J Shoulder Elbow Surg*. 2018;27(11):2068-2076. doi:10.1016/j.jse.2018.05.020
5. Millard N, DeMoss A, McIlvain G, Beckett JA, Jasko JJ, Timmons MK. Wrist flexion exercise increases the width of the medial elbow joint space during a valgus stress test. *J Ultrasound Med*. 2019;38(4):959-966. doi:10.1002/jum.14779
6. Park MC, Ahmad CS. Dynamic contributions of the flexor-pronator mass to elbow valgus stability. *J Bone Joint Surg Am*. 2004;86(10):2268-2274. doi:10.2106/0004623-200410000-00020
7. Udall JH, Fitzpatrick MJ, McGarry MH, Leba TB, Lee TQ. Effects of flexor-pronator muscle loading on valgus stability of the elbow with an intact, stretched, and resected medial ulnar collateral ligament. *J Shoulder Elbow Surg*. 2009;18(5):773-778. doi:10.1016/j.jse.2009.03.008
8. Digiovine NM, Jobe FW, Pink M, Perry J. An electromyographic analysis of the upper extremity in pitching. *J Shoulder Elbow Surg*. 1992;1(1):15-25. doi:10.1016/s1058-2746(09)80011-6
9. Saito A, Namiki Y, Okada K. Elasticity of the flexor carpi ulnaris muscle after an increased number of pitches correlates with increased medial elbow joint space suppression. *J Strength Cond Res*. 2021;35(9):2564-2571. doi:10.1519/jsc.0000000000004090
10. Camp CL, Tubbs TG, Fleisig GS, et al. The relationship of throwing arm mechanics and elbow varus torque: within-subject variation for professional baseball pitchers across 82,000 throws. *Am J Sports Med*. 2017;45(13):3030-3035. doi:10.1177/0363546517719047
11. Okoroa KR, Meldau JE, Lizzio VA, et al. Effect of fatigue on medial elbow torque in baseball pitchers: a simulated game analysis. *Am J Sports Med*. 2018;46(10):2509-2513. doi:10.1177/0363546518782451
12. Mullaney MJ, McHugh MP, Donofrio TM, Nicholas SJ. Upper and lower extremity muscle fatigue after a baseball pitching performance. *Am J Sports Med*. 2005;33(1):108-113. doi:10.1177/0363546504266071
13. Mullaney MJ, McHugh MP, Kwiecien SY, Ioviero N, Fink A, Howatson G. Accelerated muscle recovery in baseball pitchers using phase change material cooling. *Med Sci Sports Exerc*. 2021;53(1):228-235. doi:10.1249/mss.0000000000002447
14. Tyler TF, Thomas GC, Nicholas SJ, McHugh MP. Addition of isolated wrist extensor eccentric exercise to standard treatment for chronic lateral epicondylitis: a prospective randomized trial. *J Shoulder Elbow Surg*. 2010;19(6):917-922. doi:10.1016/j.jse.2010.04.041
15. Remaley DT, Fincham B, McCullough B, et al. Surface electromyography of the forearm musculature during the windmill softball pitch. *Orthop J Sports Med*. 2015;3(1):232596711456679. doi:10.1177/2325967114566796
16. Zipp P. Recommendations for the standardization of lead positions in surface electromyography. *Europ J Appl Physiol*. 1982;50(1):41-54. doi:10.1007/bf00952243
17. Kendall FP, Kendall McCreary E, Provance PG, Rodgers M, Romani W. *Muscles: Testing and Function, with Posture and Pain*. Wolters Kluwer Health; 2014.
18. Agre JC, Magness JL, Hull SZ, et al. Strength testing with a portable dynamometer: reliability for upper and lower extremities. *Arch Phys Med Rehabil*. 1987;68:454-458.
19. Hoshika S, Nimura A, Takahashi N, Sugaya H, Akita K. Valgus stability is enhanced by flexor digitorum superficialis muscle contraction of the index and middle fingers. *J Orthop Surg Res*. 2020;15(1):121. doi:10.1186/s13018-020-01640-7

20. Pexa BS, Ryan ED, Myers JB. Medial elbow joint space increases with valgus stress and decreases when cued to perform a maximal grip contraction. *Am J Sports Med.* 2018;46(5):1114-1119. doi:10.1177/0363546518755149

21. Slowik JS, Aune KT, Diffendaffer AZ, Cain EL, Dugas JR, Fleisig GS. Fastball velocity and elbow-varus torque in professional baseball pitchers. *J Athl Train.* 2019;54(3):296-301. doi:10.4085/1062-6050-558-17

22. Reinold MM, Macrina LC, Fleisig GS, Aune K, Andrews JR. Effect of a 6-week weighted baseball throwing program on pitch velocity, pitching arm biomechanics, passive range of motion, and injury rates. *Sports Health.* 2018;10(4):327-333. doi:10.1177/1941738118779909