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Relationship Between the Medial Elbow Adduction Moment During Pitching and Ulnar Collateral Ligament Appearance During Magnetic Resonance Imaging Evaluation

Wendy J. Hurd,*† PT, PhD, SCS, Kenton R. Kaufman,† PE, PhD, and Naveen S. Murthy,† MD, R-D
Investigation performed at Mayo Clinic, Rochester, Minnesota

Background: Medial elbow distraction during pitching as the primary mechanism contributing to adaptations in ulnar collateral ligament (UCL) appearance during magnetic resonance imaging (MRI) evaluation has not been established.

Hypothesis: Uninjured high school–aged pitchers with unilateral adaptations of the UCL exhibit a higher peak internal elbow adduction moment than those without UCL adaptations.

Study Design: Cohort study (Prevalence); Level of evidence, 2.

Methods: Twenty uninjured, asymptomatic high school–aged pitchers underwent bilateral elbow MRI examinations. Three-dimensional motion analysis testing was performed to collect throwing arm biomechanics as participants pitched from an indoor mound. Nonparametric tests were performed to compare peak internal elbow adduction moment in uninjured participants with and without adaptations in UCL appearance and to determine the nature of the relationship between the peak internal adduction moment and UCL appearance.

Results: Uninjured participants with UCL thickening exhibited a higher peak internal elbow adduction moment of 53.3 ± 6.8 N·m compared with uninjured participants without adaptations in UCL appearance, 38.8 ± 10.9 N·m (P = .05), as higher moments were correlated with ligament thickening (correlation coefficient, 0.45) (P = .02).

Conclusion: This study establishes the association between medial elbow distraction captured by the internal adduction moment during pitching and UCL adaptations visible during MRI evaluation.

Keywords: overhead athlete; MRI; ulnar collateral ligament; joint kinetics; youth athlete

Injuries involving the ulnar collateral ligament (UCL) are common at all levels of play in the sport of baseball.[6,7] The cause of injury is frequently attributed to cumulative microtrauma.[28,29] During pitching, the medial elbow must combat an external distraction force. Previous biomechanical studies have reported this as a varus torque ranging from 64 to 120 N·m.[10,26] Fleisig et al[10] suggested that this distraction stresses the UCL to its ultimate tensile limit with each pitch. The theory was based on a report that approximately 55% of the resistance to distraction comes from the UCL when the elbow is flexed to 90°[20] and cadaveric data describing the point of failure for the UCL at 32 N·m.[9] Fleisig et al[10] subsequently concluded that the varus torque experienced during pitching was a "critical load" related to elbow injuries.

Biomechanical calculation of the resistance to medial elbow distraction during pitching, reported as a varus torque or internal adduction moment, has been inferred as a marker of UCL tissue strain.[2,5,17] The resistance provided to combat this distraction, however, is provided by multiple ligamentous, capsular, and osseous tissue structures. The relative contribution to joint stability provided by each of these anatomic entities varies by the elbow flexion angle.[20] Additional contributions to elbow stability provided by dynamic musculotendinous contractions have not been quantified but are believed to play a meaningful role in preserving joint integrity. Thus, the UCL is not the only structure experiencing stress during valgus loading. Fleisig et al[11] proposed muscle strain, avascular necrosis, osteochondritis dissecans, and osteochondral chip

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

†Mayo Clinic, Rochester, Minnesota.

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fractures along with UCL tearing as potential injuries associated with medial elbow distraction. Based on elbow anatomy, these are all reasonable scenarios. Identifying a biomechanical variable as a marker of UCL strain may provide insight into the cause and progression of a common baseball injury.

The purpose of this investigation was to assess the association between medial elbow distraction during pitching as measured during 3-dimensional motion analysis testing and UCL appearance during MRI evaluation. We hypothesized that uninjured, asymptomatic high school–aged pitchers with unilateral adaptations of the UCL during MRI evaluation would exhibit greater medial elbow distraction during pitching, represented by the internal elbow adduction moment, than asymptomatic pitchers without adaptations in UCL appearance.

MATERIALS AND METHODS

Participant consent and parental assent were obtained before initiating the testing protocol, which was approved by the Mayo Clinic Institutional Review Board. Study procedures included an upper extremity examination performed by a board-certified physical therapist (W.J.H.), completion of a QuickDASH self-assessment of upper extremity function questionnaire, MRI examination, and a 3-dimensional analysis of the pitching motion.

Participants

All participants were required to have a minimum of 3 consecutive years of pitching experience, aged between 14 and 19 years, and a willingness to participate in all testing activities. Participants were also required to be unrestricted in baseball participation at the time of testing (QuickDASH sports score $\geq$90%), have no current injury to either upper extremity as determined by the upper extremity examination, and have no history of elbow injury in either extremity. Individuals were not eligible to participate in the study if they failed to meet any of the participation criteria.

MRI Procedures

Image acquisition was performed using a 1.5-T magnetic resonance unit (General Electric Medical Systems, Milwaukee, Wisconsin) with a dedicated institutionally developed birdcage extremity surface coil. During testing, participants were prone with their arm positioned above their head, keeping the elbow in the center of the magnet. Bilateral evaluation of the ulnar collateral ligament appearance was performed using images obtained in the coronal plane (slice thickness 3 mm/spacing 0.5 mm) using fast-spin echo proton density and T2-weighted fat saturated sequences. Ligament appearance was graded using a binomial scale and graded as either normal or abnormal in appearance based on the presence of thickening, signal heterogeneity, and discontinuity.[24] Each image was read by the same board-certified, fellowship-trained, musculoskeletal radiologist (N.S.M.) who was blinded to all participant data, including the throwing limb.

Three-Dimensional Pitching Analysis

Upper extremity kinematics was collected with a 10-camera Motion Analysis EVa RealTime system (Motion Analysis Corp, Santa Clara, California). Kinematic data were sampled at 500 Hz, and marker data were low-pass filtered at 6 Hz with a fourth-order zero lag Butterworth filter.

Data collections consisted of 10 fastballs thrown for strikes. Participants threw from an indoor pitching mound to a target 18.4 m away. An examiner positioned behind the net recorded pitch velocity using a radar gun (Jugs Sports, Tualatin, Oregon). To prepare for the testing, all participants performed a 5- to 10-minute warm-up consisting of stretching, jogging, and light tossing activities. Retro-reflective markers were then secured directly to the skin with tape and liquid adhesive. Participants were acclimated to pitching from the mound with the markers in place before test trials were collected.

Reflective markers were placed on the participant's trunk (spinous process of the seventh cervical vertebrae, sternal notch, and xiphoid process) and throwing arm (the lateral second metacarpal head, medial fifth metacarpal head, radial and ulnar styloid processes, medial and lateral epicondyles of the elbow, and acromion process) to identify anatomic landmarks, calculate joint centers and segment length, and track segment motion. A static reference position was captured with the upper extremities in an anatomic neutral position to define joint axes. Calculations were based on a 3-dimensional kinematic model previously described.[21] A 3-dimensional model of the upper extremity was developed using Visual3D (C-Motion, Inc, Germantown, Maryland) and consisted of rigid body segments, including the trunk, upper arm, lower arm, and hand. Joint kinetics was derived using inverse dynamics.[16] The inertial properties[8] of the segments were input into the model. To determine the force applied by the baseball to the hand, the impulse-momentum relationship was used with the baseball, which was modeled as a 142-g mass. The point of force application on the hand was assumed to be the midpoint between the second and fifth metacarpals.

Data Analysis

For statistical analysis, the biomechanical variable of interest was the throwing elbow peak internal adduction moment normalized to participant height and mass. We normalized the moment to participant height and mass to eliminate the influence of body dimensions and permit between-subject comparisons. Many investigators, however, have chosen to report nonnormalized kinetic data.[1,10,11,25-27] Therefore, we also reported the nonnormalized internal adduction moment to facilitate between-study comparisons. Statistical analysis was not performed on the nonnormalized data.

Figure 1. Dominant (A) and nondominant (B) MRI images for an uninjured participant without unilateral adaptations in ulnar collateral ligament (UCL) appearance. Arrows denote symmetrical UCL appearance.

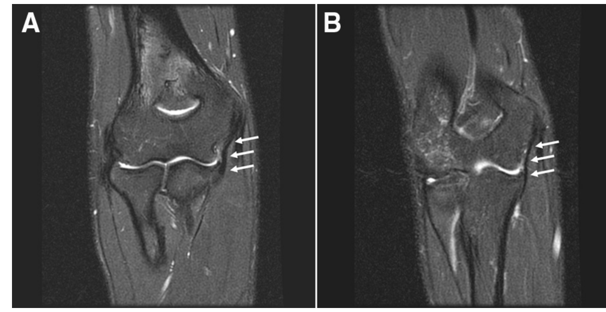

Figure 2. Dominant (A) and nondominant (B) MRI images for an uninjured participant with unilateral adaptations in ulnar collateral ligament (UCL) appearance. Arrows denote asymmetrical UCL appearance.

The peak moment was identified by visual inspection of the entire pitching cycle. The value for each trial was recorded, and the average of the 10 trials was averaged and used for analysis. Uninjured participants were allocated to 1 of 2 groups based on whether they had normal (symmetrical ligament appearance on bilateral comparison, homogeneous signal, and no discontinuity) or abnormal UCL appearance (asymmetrical thickening, signal heterogeneity, or discontinuity) for the throwing elbow. Nonparametric statistical testing was performed secondary to the small, unequal sizes of the groups and the categorical nature of the UCL grading system. The relationship between the peak internal elbow adduction moment and UCL appearance was evaluated with a bivariate correlation test (Spearman rho). The peak internal elbow adduction moment and participant characteristics for each group (age, years of pitching experience, pitch velocity) were compared with a Mann-Whitney *U* test. Statistical significance was established at $\alpha \leq 0.05$. All statistical tests were performed using commercially available software (SPSS 15.0; SPSS, an IBM Company, Chicago, Illinois).

RESULTS

Among uninjured participants, 7 exhibited normal (Figure 1) and 13 exhibited abnormal (Figure 2) UCL appearance. All participants with abnormal UCL appearance exhibited ligament thickening of the pitching arm on bilateral comparison. No participants demonstrated signal heterogeneity or ligament discontinuity, and no participants had fully open growth plates.

The 2 groups were not different for age at the time of testing, number of years experience as a pitcher, or mean pitch velocity (Table 1). The peak internal adduction moment was significantly different between groups, as the participants with abnormal UCL appearance exhibited higher moments (Table 2) ($P = .05$). There was also a statistically significant, positive relationship between the magnitude of the peak internal adduction moment and UCL appearance (correlation coefficient, 0.45; $P = .02$).

DISCUSSION

This study establishes an association between tissue adaptations of the anterior band of the UCL identified during MRI evaluation as a response to the medial elbow distraction experienced during pitching. In 2 comparable groups of asymptomatic pitchers in terms of age and years of playing experience, those presenting with unilateral UCL thickening of the throwing elbow exhibited a significantly greater internal adduction moment compared with those with symmetrical UCL appearance. The interpretation of the tissue adaptation in this asymptomatic population remains unclear. It is possible ligament thickening represents a positive adaptation, with unilateral thickening equating with a stronger ligament.[24] Conversely, the unilateral thickening apparent in this young group may represent the initiation of a degenerative UCL tear that does not become symptomatic until adulthood. In the absence of prospective, longitudinal studies, it is unclear what these adaptations represent beyond a response to the repetitive stresses associated with pitching.

Tissue adaptations of the throwing elbow have been described in asymptomatic throwers from youth through professional levels of play.[14,17,22,23] Kooima et al[17] reported that of 16 asymptomatic major league players, 14 demonstrated UCL abnormalities that were visible on MRI. In earlier work, we identified asymmetrical thickening of the UCL in 65% (15/23) of uninjured high school–aged pitchers.[13] These changes in ligament appearance have been attributed to chronic exposure to stress and considered a normal finding in the overhead athlete in the absence of symptom complaints.[17] Thus, these MRI findings must be interpreted in context with the player's history and physical examination when the athlete presents with complaints.[17]

An association between the medial elbow distraction forces experienced during pitching and injury has been described in adult pitchers. Anz et al[3] calculated elbow kinetics obtained from a videotaped pitching analysis in 23 professional pitchers and subsequently tracked injuries during the next 3 competitive seasons. In this sample, 9 players went on to sustain an elbow injury. The authors reported differences in peak external elbow valgus torque that approached statistical significance when comparing

TABLE 1
Group Demographics[a]

	Normal UCL Appearance, Mean (Range)	Abnormal UCL Appearance, Mean (Range)	*P* Value
Age at testing, y	16 (15-16)	16 (15-19)	.13
Pitching experience, y	6 (3-10)	6 (3-11)	.84
Pitch velocity, miles/h	69 (63-81)	74 (69-81)	.08

[a]UCL, ulnar collateral ligament.

TABLE 2
Peak Internal Adduction Moment[a]

	Normalized, Nm/mass·ht, Mean (SD)	Nonnormalized, Nm, Mean (SD)
Normal UCL appearance	0.498 (0.09)[b]	38.8 (10.9)
Abnormal UCL appearance	0.588 (0.04)[b]	53.3 (6.8)

[a]UCL, ulnar collateral ligament.
[b]$P < .05$.

injured (98.8 N·m) and uninjured pitchers (91.1 N·m), as well as a significant correlation of elbow injury with higher elbow valgus torque during the late cocking phase.[3] Anz et al[3] concluded that these data indicated higher levels of torque can result in an increased injury risk, and manipulation of pitching mechanics to alter this torque may help decrease injury rates. Additional work will be necessary, however, to determine the magnitude at which elbow valgus torque becomes a risk factor for subsequent injury.

The average peak elbow adduction moment during pitching for participants in this study is comparable with previously reported values. Fleisig et al[11] evaluated pitching kinetics and kinematics in uninjured baseball pitchers from youth to professional levels of play. The high school group, consisting of 33 participants ranging from 15 to 20 years, exhibited an average peak internal elbow varus torque of 48 N·m.[11] The magnitude of the peak varus torque in the high school–aged pitchers was significantly greater than youth pitchers (28 N·m) and significantly less than collegiate (55 N·m) and professional (64 N·m) pitchers. The authors concluded that because there were no differences in kinematic or timing characteristics across the different age groups, the progressive increase in joint kinetics was a consequence of increases in strength and muscle mass associated with increasing age.[11] We partially agree with this conclusion. Increases in muscle mass typically accompany an increase in whole body mass and height, which are components of kinetic calculations. The values reported by Fleisig et al[11] did not implement anthropometric normalization. Failure to normalize kinetic values obtained during 3-dimensional motion analysis studies limits the ability to make valid comparisons across participants, as differences in nonnormalized data may be a consequence of body dimensions and not biomechanical characteristics.[12,19]

The effect of normalized data is illustrated in a study by Sabick et al,[25] who evaluated elbow valgus torque in 14 youth pitchers who were on average age 12 years. Sabick et al reported a mean peak elbow valgus torque for the group of 18 N·m with body weight the strongest predictor of valgus torque (61% of variability). After subsequently controlling for body size, the authors identified the most significant biomechanical contributors to elbow valgus torque as maximum shoulder abduction and shoulder internal rotation torque.[25] By normalizing kinetic values, we are able to evaluate the association between UCL appearance and the peak elbow adduction moment as a function of pitching mechanics and not body dimensions.

This was not an exhaustive investigation of factors contributing to UCL tissue adaptations. Although the current study identified an association between the magnitude of the internal elbow adduction moment and UCL appearance, symptomatic tears in throwers have been attributed to repetitive trauma.[15,22] Thus, the volume of throwing an athlete performs is likely to also contribute to tissue adaptations. We did not identify a difference in age among athletes with and without unilateral UCL thickening. Age may not, however, accurately reflect the volume of throwing an athlete has experienced. Pitch type has also been associated with elbow injury, with breaking pitches hypothesized to introduce greater loading to joints than a fastball or change-up pitch. The potential effect of both pitch volume and pitch type on tissue adaptations is supported by a study by Lyman et al,[18] who reported a significant correlation between the number of pitches thrown in a game and over the course of a season and the rate of elbow pain among youth pitchers. The investigators also reported that throwing a slider was associated with an 86% increased risk of elbow pain.[18] Finally, pitch velocity has been associated with elbow injury in professional baseball athletes. In a prospective study, Bushnell et al[4] reported that uninjured pitchers who subsequently sustained an elbow injury threw on average 4 mph faster than pitchers who did not experience elbow injury. In the current investigation, there was a 5-mph difference between groups with and without UCL adaptations. Although this did not reach statistical significance, the work by Bushnell et al[4] suggests the difference may be clinically meaningful. On the basis of the results of these studies, it is reasonable to conclude that adaptations in UCL appearance are likely to be multifactorial.

CONCLUSION

Greater medial elbow distraction forces during pitching are associated with adaptations in UCL appearance during

MRI evaluation in uninjured pitchers. These findings provide a biomechanical rationale for imaging findings in the throwing population. The long-term implications of tissue adaptations in response to medial elbow distraction among asymptomatic athletes must be evaluated with prospective, longitudinal studies.

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