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APPLIED SCIENCES

Varus Strength of the Medial Elbow Musculature for Stress Shielding of the Ulnar Collateral Ligament in Competitive Baseball Pitchers

TOSHIMASA YANAI[1], KENGO ONUMA[2], and TOMOYUKI NAGAMI[3]

[1]*Research Institute of Baseball Science and Faculty of Sport Sciences, Waseda University, Tokorozawa City, Saitama, JAPAN;* [2]*Graduate school of Sport Sciences, Waseda University, Tokorozawa City, Saitama, JAPAN; and* [3]*College of Liberal Arts and Sciences, Kitasato University, Sagamihara City, Kanagawa, JAPAN*

ABSTRACT

YANAI, T., K. ONUMA, and T. NAGAMI. Varus Strength of the Medial Elbow Musculature for Stress Shielding of the Ulnar Collateral Ligament in Competitive Baseball Pitchers. *Med. Sci. Sports Exerc.*, Vol. 57, No. 4, pp. 791–799, 2025. **Purpose:** Valgus load opens the medial elbow compartment, causing elongation of the ulnar collateral ligament (UCL) that can eventually lead to attenuation and failure. Ideally, the muscles surrounding the medial aspect of elbow joint should coordinate medial elbow compression to prevent the medial elbow compartment from opening and loading the UCL. This study aimed to determine whether baseball pitchers have sufficient elbow varus strength to unload the UCL during pitching. **Methods:** Using an electromagnetic tracking device, we measured the peak elbow varus moment during pitches (fastball, slider, curveball, and changeup) by 14 professional and 8 collegiate pitchers. Elbow varus strength was measured with an isokinetic dynamometer system while the medial elbow joint space was monitored using ultrasonography. A paired *t*-test was used to compare the peak varus moment generated during pitching with the varus strength, and the relative intensity of muscular output required to unload the UCL was determined. **Results:** Except for curveballs, the muscular varus strength (57.5 ± 9.2 N·m) was not significantly larger ($P = 0.165$–0.853) than the peak varus moments during pitching (55.4 ± 13.0 N·m). Ten participants did not have sufficient muscular varus strength to completely unload the UCL from valgus loading when throwing fastballs and other pitch types. The relative intensity of muscular torque output required for stress shielding of the UCL ranged from 89.1% ±21.7% maximum voluntary isometric varus strength (MVIVS) for curveballs to 103.1% ±26.5% MVIVS for fastballs. **Conclusions:** Our findings demonstrate that most of the valgus load on the elbow joint during pitching can be counteracted by the muscular varus moment, but valgus loading on the UCL is likely unavoidable in baseball pitching. **Key Words:** BIOMECHANICS, FLEXOR–PRONATOR MUSCLE MASS, INVERSE DYNAMICS, LIGAMENTOUS INJURY, THROWING

During baseball pitching, the resultant elbow varus moment reaches a peak value of 50–120 N·m near the end of the cocking phase (1–10). This varus moment is produced by a combination of tensile forces of the ulnar collateral ligament (UCL) and joint capsule (11,12), compressive forces on the bones of the lateral side of the elbow joint (11,12), and contractile forces of the medial elbow musculature (11,13–17) in order to resist the motion-dependent valgus load acting on the elbow joint (Fig. 1). The structural strength of the static stabilizers of the elbow joint is far too low to withstand the motion-dependent valgus loads in baseball pitching. Cadaveric studies have revealed that a dissected elbow joint with all muscles removed can withstand a valgus load of up to 35 N·m before joint failure (18,19). A synergistic muscular contribution is necessary to meet the demands on the pitcher's elbows in order to pitch safely.

Anatomical and biomechanical studies have demonstrated that a muscular varus moment can be generated by the elbow flexor–pronator muscle group, which includes the flexor carpi ulnaris, flexor digitorum superficialis, and pronator teres (11,14–17,20,21). These muscles, which surround the medial

Address for correspondence: Toshimasa Yanai, PhD, 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192, Japan; E-mail: tyanai@waseda.jp.
Submitted for publication February 2024.
Accepted for publication November 2024.

0195-9131/25/5704-0791/0
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DOI: 10.1249/MSS.0000000000003614

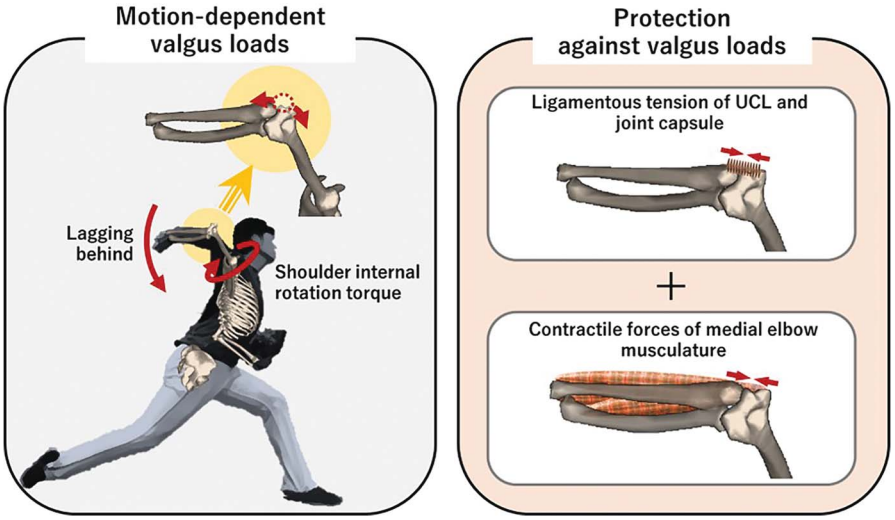


FIGURE 1—Schematic representation of valgus angulation of elbow joint due to motion-dependent valgus loading during pitching and the forces that generate varus moment to counteract valgus loading. Motion-dependent valgus loads may open up the medial joint compartment and cause valgus angulation of the elbow joint. If the UCL and medial joint capsule are elongated beyond the resting length due to valgus angulation, they develop ligamentous tension to resist farther opening of the medial joint compartment. Medial elbow musculature coordinates compressive force to prevent opening of the medial elbow compartment caused by valgus loading. Reprinted from Journal of Biomechanics, 147/111427 Kengo Onuma and Toshimasa Yanai, A method for measuring muscle strength in restraining valgus joint angulation: elbow varus muscle strength against valgus loading, Copyright (2023), with permission from Elsevier.

aspect of elbow joint, can coordinate medial elbow compression and resist opening of the medial elbow compartment caused by valgus loading. The synergistic function of the medial elbow musculature in assisting the UCL to restrain valgus angulation against valgus overloading has been confirmed in laboratory studies (11,14–17,20,21), and the concept of dynamic stabilization to counter valgus loading to protect the UCL during baseball pitching (14) is recognized widely (22). However, it is not known whether baseball pitchers' elbow musculature is strong enough to provide stress shielding of the UCL during pitching. It is also not clear how strongly the musculature must contract to completely unload valgus loading on the UCL or to reduce the loading to within a safe range. Such information is essential for assessing each baseball pitcher's elbow injury risk and designing an individualized conditioning/rehabilitation program to prevent elbow injuries.

Recently, an experimental method was introduced to measure the strength of the medial elbow musculature in restraining valgus angulation (23). This method uses an isokinetic dynamometer in a standard setting for shoulder internal rotation exercises (Fig. 2a). With the elbow flexed at 90° and the humerus aligned with the axis of the dynamometer, the torque output from the dynamometer indicates the internal rotation torque of the shoulder as well as the varus torque of the elbow produced by the medial elbow musculature and the static stabilizers of the elbow joint. The largest internal rotation torque recorded before

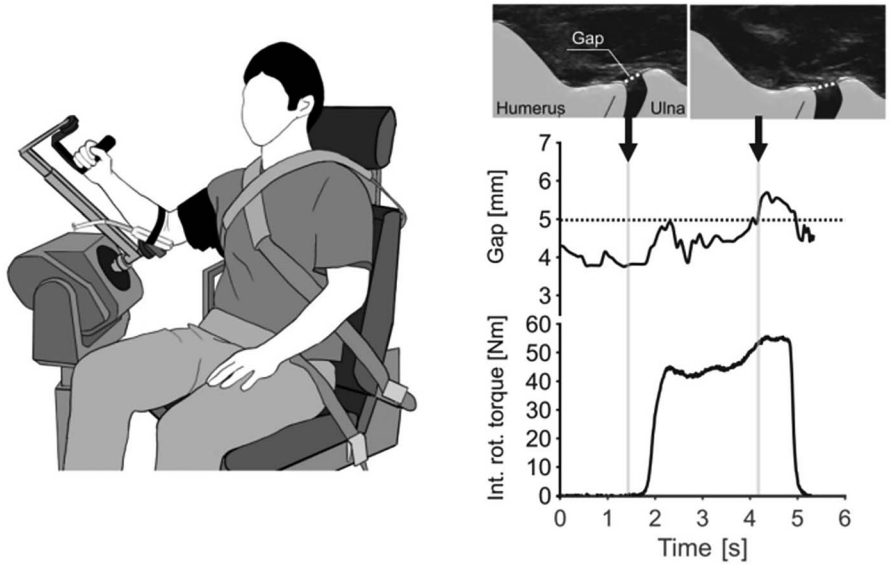


FIGURE 2—Experimental setup for measurement of muscular varus strength with an isokinetic dynamometer and ultrasound device (a) and the response of a participant who showed a widening of the gap during ramp contraction of the shoulder internal rotator muscles (b). (These figures are reproduced from an open-access article published in Onuma and Yanai (23).

the humeroulnar joint space was widened (Fig. 2b) was determined as the elbow varus strength, which was found to be 41 ± 12 N·m in 20 healthy young men. In a previous study, this dynamometry method was applied to two postoperative baseball pitchers (24) and their muscular varus strengths (71 and 59 N·m) were found to be higher than the peak varus moments recorded during fastball pitching (63 ± 3 and 54 ± 6 N·m, respectively). In addition, this study found that the muscular varus moment required to keep the valgus load on the UCL within a safe range during pitching was 39%–63% of the muscular varus strength depending on the type of pitch. Muscular varus strength appears to vary substantially between individuals, suggesting that some pitchers may not have sufficient muscular varus strength to unload the UCL and that insufficient muscular varus strength might be a risk factor for valgus overload injuries. However, those findings on muscular varus strength are preliminary and not adequately generalizable to confirm whether baseball pitchers' elbow musculature can function as the sole contributor for stress shielding of the UCL. Therefore, the present study was conducted to quantify the relative intensity of muscular contractile output required to unload the UCL during pitching and to examine the stress-shielding capability of the elbow musculature in a group of healthy baseball pitchers playing at a highly competitive level. This study tested the hypothesis that the varus strength of elbow muscles is larger than the peak varus moment reached during pitching delivery.

METHODS

Fourteen professional baseball pitchers (age: 21.9 ± 2.7 yr; body mass: 82.8 ± 5.3 kg; height: 1.81 ± 0.05 m) and eight collegiate pitchers (age: 19.4 ± 1.4 yr; body mass: 77.1 ± 3.0 kg; height: 1.78 ± 0.03 m) participated in this study. Nine participants had experienced shoulder or elbow pain at least once in the past 3 yr of their baseball careers, and four of them (all professional pitchers) had undergone UCL reconstruction more than a year and a half before this study. All participants were self-declared as healthy and as having no physical injury or pain on the experimental days that would hinder their normal pitching performance. The study procedure was approved by the institutional Ethics Review Committee on Research with Human Subjects. The risks and benefits associated with voluntary participation were explained to each participant, and their informed consent was obtained in writing. All aspects of the study were conducted in accordance with the standards of the Declaration of Helsinki.

The data collection procedure comprised two parts: (a) assessment of the maximum voluntary isometric strength of the medial elbow musculature (23) and (b) motion analysis of the pitching delivery (24,25) in order to determine the peak resultant varus moment generated at the elbow. The two parts were conducted on different days.

On day 1, an isokinetic dynamometer (Biodex System 4; Biodex Medical Systems, New York, NY) and an ultrasound device (ArtUs EXT-1H; TELEMED Ultrasound Medical Systems, Vilnius, Lithuania) were used to measure the maximum voluntary isometric strength (Fig. 3), as described previously (23). These devices were gen-locked so that the synchronized output data set could be subsequently analyzed to isolate the muscular contribution to torque production. Each participant was positioned in a standardized posture for shoulder internal rotation exercise, with the shoulder joint abducted to 60°, horizontally adducted to 45°, and externally rotated to 60°; the elbow joint flexed to 90°; and the forearm in neutral pronation–supination. Although this body position did not mimic the pitcher's body position near the end of arm-cocking phase in baseball pitching, it allowed the participants to generate largest moments at the shoulder and elbow joints. After a few

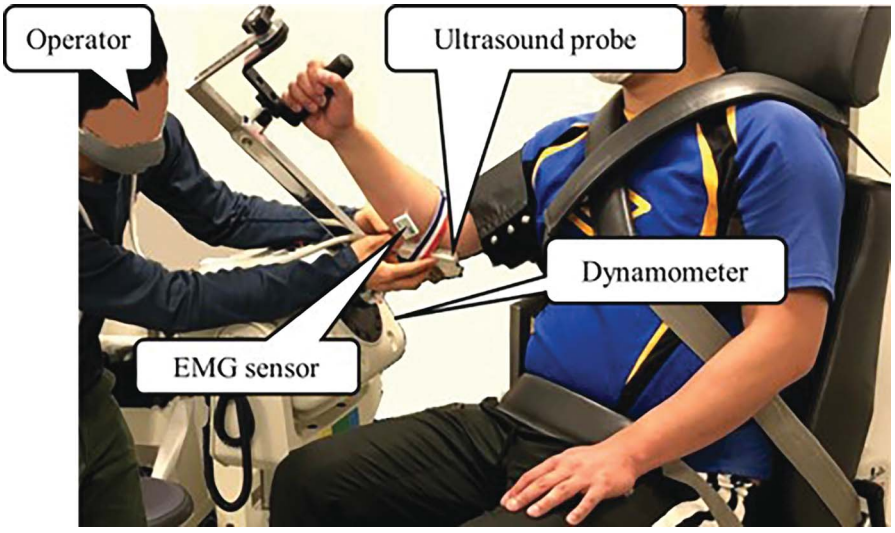


FIGURE 3—Experimental setup for the measurement of muscular varus strength. An isokinetic dynamometer system (Biodex System 4; Biodex Medical Systems) and an ultrasound device (ArtUs EXT-1H; TELEMED Ultrasound Medical Systems) were used for the measurement. Each participant was asked to perform a ramp contraction up to 100% of their maximum voluntary isometric strength of the shoulder internal rotators while maintaining the maximal voluntary isometric contractions of the flexor–pronator muscle mass. The largest torque recorded, while the medial joint space was narrower than the predetermined threshold distance, was taken as the MVIVS of the participant's elbow.

familiarization trials with slight postural adjustments to maximize comfort and force production, the participants were asked to perform a ramp contraction up to 100% of their maximum voluntary isometric strength of the shoulder internal rotation while maintaining maximal voluntary isometric contraction of the flexor–pronator muscle mass.

Because the valgus–varus axis of the elbow joint in this posture coincided with the internal–external rotation axis of the shoulder joint, the shoulder internal rotation torque measured with the isokinetic dynamometer could represent the resultant varus torque generated by all elbow structures, including the muscles, ligaments, joint capsule, and bony articulations. During the strength assessment, the width of the medial joint space from the trochlea of the humerus to the sublime tubercle of the ulna was monitored with the ultrasound device (Fig. 2b) so that the contribution of the UCL to varus torque production was identified in the subsequent analysis. An increase in the width of the medial joint space between the two bony landmarks indicates an increase in valgus angulation of the elbow joint, which causes the UCL to elongate and generate a varus moment. The medial joint width measured during the strength assessment was compared with an individualized threshold distance to identify the contribution of the UCL. The threshold distance was determined by a valgus stress test (23), in which a 0.5-kg weight was applied to the wrist of each participant in the supine position with the shoulder joint abducted to 90°, the elbow joint flexed to 90°, and the elbow muscles completely relaxed (the total valgus load applied at the elbow joint was approximately 4.5 N·m). The largest torque detected, while the medial joint width was narrower than the threshold distance, was recorded for each trial (Fig. 2b). The trial was repeated twice with a 2- to 3-min rest interval. An additional trial was conducted when the measured torque in the second trial was at least 10% higher than that of the first trial. The largest torque in the trials was taken as the maximum voluntary isometric varus strength (MVIVS) of the participant's elbow. The mean and the standard deviation of the determined torques were 56.9 ± 9.1 and 56.1 ± 9.2 N·m for the first and second trials, respectively, and the difference between the trials was 2.14 ± 2.20 N·m. The intraclass correlation was 0.949 with the 95% confidence interval of 0.883–0.978.

On day 2, pitching performances were recorded in the bullpen of the indoor baseball facility used by the player's team. Each participant underwent a self-selected warm-up session (e.g., jogging, stretching, shoulder exercises, playing catch, pitching to the catcher) and threw four pitches each for all types of pitch that they used during games. The pitch types thrown by the participants were four-seam fastball (n = 22), two-seam fastball (n = 5), curveball (n = 18), slider (n = 18), cutter (n = 9), changeup including fork balls and split-finger fastballs (n = 19), sinker (n = 2), and screw balls (n = 1). The data for four-seam fastballs, sliders, curveballs, and changeups were used for subsequent analysis. An electromagnetic tracking device (Liberty; Polhemus, Colchester, VT) was used to measure the six degrees of freedom of motion for each sensor (dimensions = 23 × 28 × 15 mm) attached to the participant's body at a nominal sampling rate of 240 Hz (24,25). One sensor was attached to the skin over the dorsal surface of the forearm of the dominant side near the wrist joint with double-sided tape and elastic tape, and another sensor was attached to a custom-made plastic cuff that was wrapped around the upper arm to minimize the influence of skin artifacts. Additional sensors were attached to the scapula and sternum to record the pitching motion. The sensor cables were bundled together and held by an operator to prevent them from interfering with the pitching motion. The ball velocity of each pitch was measured with a ball flight monitor (Rapsodo Pitching 2.0; Rapsodo LLC, Singapore).

An inverse dynamics approach was applied to determine the net varus torque at the elbow joint of the dominant side for each pitch, as previously described (24). The raw position data were smoothed with a fourth-order Butterworth filter at 15 Hz, and each body segment was modeled as a rigid body using the inertial parameters for Japanese athletes (26). The hand and ball were considered to move together with the forearm so that the ball, hand, and forearm system was modeled as a rigid body, following a previous study (27). The computed torque of the elbow joint was decomposed into three orthogonal components: flexion torque, pronation torque, and varus torque. The varus torque is the net torque exerted on the forearm by the muscles, ligaments, and other joint structures that connect the forearm and arm at the elbow joint in response to valgus loading. The peak varus moment was extracted for each pitch and expressed as a percentage with respect to the MVIVS (% MVIVS) in order to ascertain the relative intensity of the muscular output required to completely unload the UCL. In addition, the excess of the peak elbow varus moment during pitching over the muscular varus strength was computed to determine the amount of valgus load imposed on the UCL and other static stabilizers, using the following formula:

$$\text{Excess [N·m]} = \text{Peak varus moment during pitching [N·m]} - \text{MVIVS [N·m]}$$

If the MVIVS was greater than the peak varus moment during pitching and the determined value was negative, the excess of the pitch was considered to be zero.

For each pitcher and for each pitch type, the mean value of four pitches was computed for use in the statistical analysis. Shapiro–Wilk tests revealed that the peak varus moment during pitching and the MVIVS were normally distributed ($P > 0.430$). Descriptive statistics were computed as means and standard deviations. A paired t-test was used to evaluate the first hypothesis. An *a priori* power analysis using G-Power (28) showed a minimum sample size of 19 for a repeated-measures t-test with a medium effect size (0.6) and power of 80%; therefore, our sample size was considered sufficient.

RESULTS

The MVIVS was found to range from 38 to 76 N·m with a mean ± standard deviation of 57.5 ± 9.2 N·m (Table 1). For the four pitch types thrown by the participants, the peak resultant varus moment generated during pitching (53.9 ± 12.9 N·m) was attained 43.6 ± 8.8 ms before ball release (Fig. 4c). The magnitude of the peak resultant varus moment ranged from

TABLE 1. Means and standard deviations of the variables measured for each participant.

Pitcher ID[a]	Ball Speed ($m \cdot s^{-1}$)	Peak Varus Moment (N·m)	MVIVS[b] (N·m)	% MVIVS[c]
1	36.5 ± 3.1	55.6 ± 0.8	76	73.1 ± 1.0
2	33.5 ± 3.1	56.4 ± 4.9	71	79.4 ± 6.9
3	36.6 ± 3.2	55.9 ± 3.4	69	81.0 ± 4.9
4	34.4 ± 4.0	61.2 ± 2.1	69	88.6 ± 3.0
5	34.7 ± 3.4	69.1 ± 3.4	64	108.0 ± 5.4
6	32.7 ± 3.8	60.3 ± 3.0	63	95.8 ± 4.8
7	30.2 ± 5.1	47.7 ± 3.7	62	77.0 ± 6.0
8	35.5 ± 2.5	52.9 ± 2.7	60	88.1 ± 4.5
9	29.1 ± 4.3	38.8 ± 6.1	60	64.6 ± 10.1
10	37.1 ± 0.9	67.8 ± 4.1	60	112.9 ± 6.9
11	32.9 ± 2.7	46.1 ± 4.7	58	79.4 ± 8.0
12	32.3 ± 4.3	82.6 ± 10.5	58	142.4 ± 18.1
13	34.2 ± 3.5	37.5 ± 3.7	55	68.2 ± 6.8
14	34.1 ± 3.3	55.2 ± 9.0	55	100.4 ± 16.4
15	28.8 ± 4.2	43.2 ± 5.1	55	78.5 ± 9.3
16	30.3 ± 4.8	43.0 ± 3.5	52	82.8 ± 6.7
17	33.6 ± 2.8	66.5 ± 3.8	50	133.0 ± 7.5
18	32.7 ± 3.3	59.8 ± 3.6	49	122.1 ± 7.3
19	25.6 ± 2.4	29.1 ± 6.2	48	60.7 ± 13.0
20	35.1 ± 2.5	46.5 ± 3.6	47	98.9 ± 7.7
21	32.1 ± 3.1	58.5 ± 4.7	47	124.5 ± 10.1
22	32.6 ± 4.0	52.6 ± 6.7	38	138.5 ± 17.6
Mean ± SD	32.7 ± 4.0	53.9 ± 12.9	57.5 ± 9.2	96.4 ± 26.1

[a] The pitchers are numbered in descending order of muscular varus strength (Pitcher ID).
[b] MVIVS indicates the MVIVS of the medial elbow musculature.
[c] % MVIVS indicates the relative intensity of muscular varus strength required to completely resist the pitching valgus load completely and thereby unload the UCL.

49.0 ± 11.5 N·m for curveballs (ball velocity = 28.4 ± 2.8 $m \cdot s^{-1}$) to 58.1 ± 12.3 N·m for fastballs (ball velocity = 36.8 ± 2.5 $m \cdot s^{-1}$) (Fig. 5), which corresponded to 89.1% ±21.7% MVIVS to 103.1% ±26.5% MVIVS, respectively (Table 2).

The MVIVS was significantly larger ($P = 0.028$) than the peak resultant varus moment generated during pitching for only curveballs, with a 95% confidence interval of the difference ranging from 0.80 to 12.5 N·m. The peak varus moment during pitching exceeded the MVIVS in 10 participants for fastballs, 8 participants for changeups, and 6 participants for sliders and curveballs. The excess of the peak elbow varus moment during pitching over the MVIVS reached a maximum of 33.0 N·m for fastballs, 29.0 N·m for sliders, 14.6 N·m for curveballs, and 27.0 N·m for changeups (Table 2).

DISCUSSION

This study was conducted to quantify the stress-shielding capability of the elbow musculature in healthy baseball pitchers playing at a highly competitive level. The results revealed that the peak isometric elbow varus strength was not significantly larger than the peak resultant varus moment generated when throwing all types of pitches except curveballs. Therefore, the hypothesis was rejected. Nearly half the pitchers had insufficient elbow muscle strength to completely unload the UCL, and on average, the relative intensity of muscular torque output required for stress shielding of the UCL from the motion-dependent valgus loading ranged from 89.1% ±21.7% MVIVS for curveballs to 103.1% ±26.5% MVIVS for fastballs. The findings indicate that most of the valgus load on the elbow joint during pitching can be counteracted by the muscular varus moment, but valgus loading on the UCL is likely unavoidable in baseball pitching.

The large relative intensity of muscular torque output required for stress shielding of the UCL (96.4 ± 26.1% MVIVS) indicates that a near-maximum muscular output of the medial elbow musculature was required to unload the UCL during the pitching delivery. The peak resultant varus moment generated during pitching (53.9 ± 12.9 N·m) was attained 43.6 ± 8.8 ms before ball release (Fig. 4c), which was soon after the forearm was maximally leaned backward (Fig. 4b: 50.4 ± 9.0 ms before ball release) and a moment before the humeral external rotation on the thorax reached the maximum (Fig. 4d: 34.3 ± 7.3 ms before ball release). Electromyographic (EMG) studies using intramuscular fine-wire electrodes have reported that the elbow flexor–pronator muscles exhibit moderate activity (30%–50% of the maximum voluntary contraction) during the late cocking phase (same as "the arm-cocking phase") and very high activity (80%–120%) during the acceleration phase of fastball pitching (29,30). In these EMG studies, the beginning of the acceleration phase was determined not by computing shoulder joint angles, but by looking for the posture of "maximum abduction and external rotation at the shoulder" (31) on 16-mm film "on a stop-action projector" (29,30). Because the maximum layback position of the forearm in Figure 4b best characterizes such a posture, it can be assumed that the peak varus moment should be reached during the acceleration phase defined in these EMG studies. The timing of the high EMG activity of the elbow flexor–pronator muscles of the baseball pitchers reported in these studies corresponded well with the timing of peak muscular output required for complete

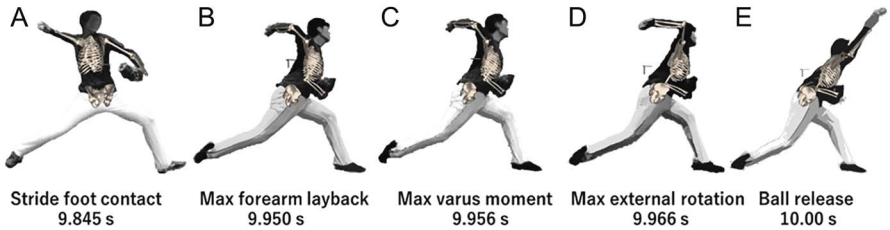


FIGURE 4—Sequence of the pitching motion during the cocking and acceleration phases of a typical pitcher. The maximum varus moment of 59.7 N·m at the elbow joint (54.9 ± 10.7 N·m for all pitchers for all pitch types) was attained 50 ms before ball release (c) (43.8 ± 8.6 ms for all pitchers). Its attainment was observed after the forearm was maximally leaned backward (b) (51.3 ± 8.0 ms for all pitchers) and before the maximum external rotation of the humerus on thorax was attained (d) (34.4 ± 7.3 ms for all pitchers). Numerical evaluation of shoulder external rotation angle yields the body position in (d) as the starting point of the acceleration phase, whereas visual evaluation of shoulder configurations may yield the body position of (b) as the starting point of the acceleration phase.

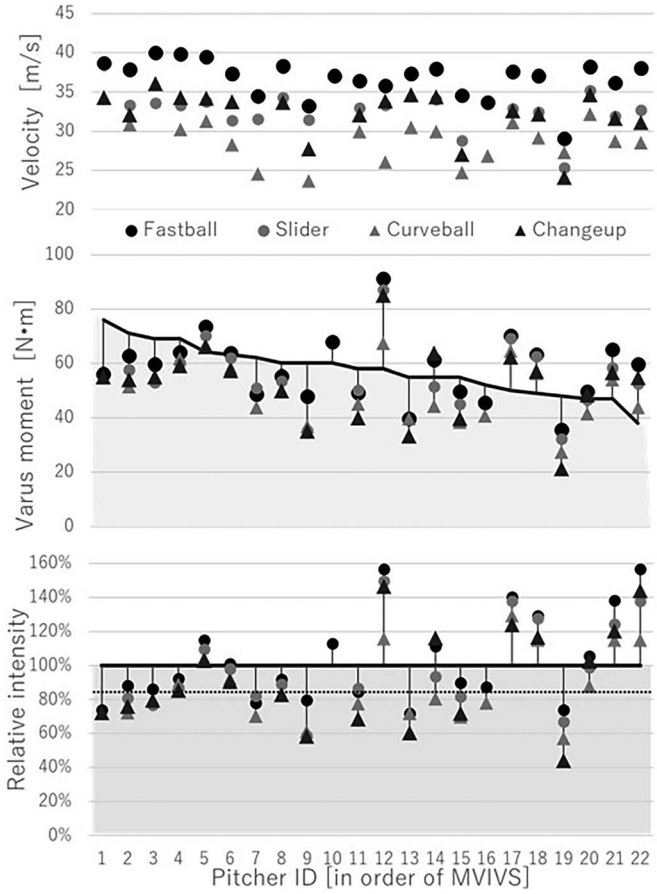


FIGURE 5—Muscular varus strength and peak varus moment generated during pitching of fastballs, sliders, curveballs, and changeups for all participants. On the horizontal axis, the pitchers are numbered in descending order of muscular varus strength (Pitcher ID).

unloading of the UCL as determined in this study. This correspondence, however, does not guarantee that the amount of muscle forces/torques exerted by these muscles at that instant was also at near-maximal to supramaximal levels. This is primarily due to the fact that the muscle's length, contraction velocity, fatigue level, and presence of pre-stretching and/or pre-tension are not identical between the pitching and isometric varus strength test used in the present study. Because the pitching motion has been shown to involve a clear pattern of proximal-to-distal sequence of the scapula, arm, and forearm rotations (25), there should be pre-stretching and pre-tension in the muscles involved, and the flexor–pronator muscles should be in a condition to generate greater force/torque for a given level of stimulation. Although it is unknown whether these muscles actually produced near-maximal or supramaximal amount of forces/torques, it could be postulated that the medial elbow musculature generated a substantial amount of muscular varus moment during pitching delivery to resist the motion-dependent valgus loads on the elbow joint and to prevent valgus overloading of the UCL.

More than half of the participants (n = 12) had muscular varus strength sufficient for stress shielding of the UCL. Our findings indicate that relatively large valgus loads can be applied to the pitcher's elbow during the pitching motion before the UCL is tensed, if the flexor–pronator muscles are highly active. This is unlike the previous cadaveric studies where any amount of valgus load would result in elongation of the UCL. However, even for these 12 participants, the relative intensity of muscular torque output required to unload the UCL was substantial, reaching up to 93% MVIVS for fastball, 89% MVIVS for slider and curveball, and 86% MVIVS for changeup (Fig. 5). Considering that the strength of the medial elbow musculature should gradually decrease over 7 innings of 15 pitches by approximately 12% as an experimental study reported (32), the musculature of some participants is unlikely to be able to produce the full varus torque required to completely unload the UCL in repeated pitching across multiple innings (Fig. 6:

TABLE 2. Means and standard deviations of the variables measured for each pitch type.

Pitch Type	Ball Speed ($m \cdot s^{-1}$)	Peak Varus Moment (N·m)	% MVIVS[a]	Excess[b] (N·m)	Max. Excess (N·m)
Fastball	36.8 ± 2.5	58.1 ± 12.3	103.1 ± 26.5	6.1 ± 9.5	33.0
Slider	32.4 ± 2.2	55.4 ± 12.7	99.4 ± 26.2	5.2 ± 8.7	29.0
Curve ball	28.4 ± 2.8	49.0 ± 11.5	89.1 ± 21.7	2.6 ± 4.3	14.6
Changeup	32.4 ± 3.0	52.3 ± 14.1	92.9 ± 29.0	4.5 ± 7.5	27.0
Mean ± SD	32.7 ± 4.0	53.9 ± 12.9	96.4 ± 26.1	4.7 ± 7.8	

[a] % MVIVS indicates the relative intensity of muscular varus strength required to completely resist the pitching valgus load completely and thereby unload the UCL.
[b] Excess is the surplus of the peak varus moment attained during pitching over the MVIVS, which is indicative of the valgus load imposed on the static stabilizers of elbow joint. The excess of a given pitch was considered to be zero, if the MVIVS was greater than the peak varus moment during pitching.

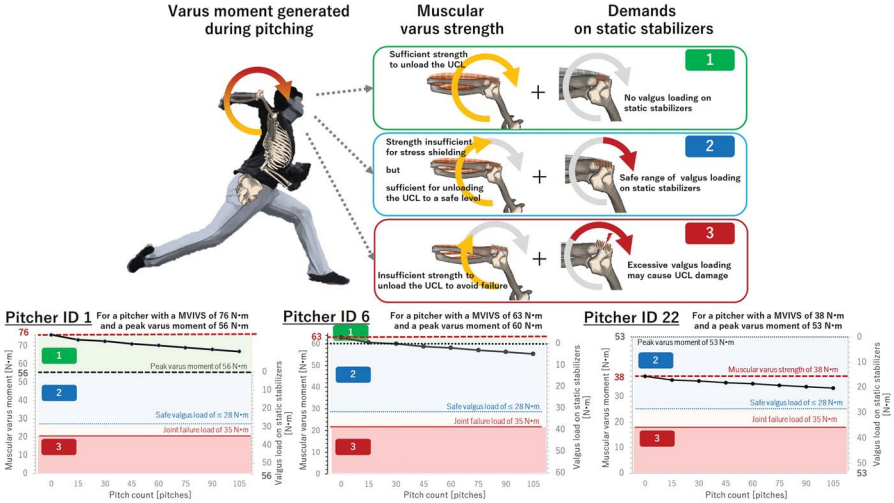


FIGURE 6—Schematic representation of the elbow varus moment during pitching and graphical representations of the relation between the MVIVS and pitch count estimated from the forearm strength data in repetitive pitching presented by Namiki et al. (32). When muscular varus strength exceeds the peak varus moment during pitching, the UCL and other static stabilizers can be unloaded completely. However, when muscular varus strength is low due to insufficient strength, fatigue, lack of conditioning, or injury such that it cannot unload the UCL to avoid a joint failure load of 35 N·m (18,19), an excessive valgus load placed on the joint can result in a UCL injury. Theoretically, UCL injury can be avoided if the medial elbow musculature produces a sufficient muscular varus moment to unload the UCL to a safe level, which is estimated to be 28 N·m (24), from a joint failure load of 35 N·m (18,19) multiplied by an upper limit of the elastic range of 80% (33). For Pitcher ID 1, stress shielding of the UCL is possible for more than 100 pitches. For Pitcher ID 6, stress shielding of the UCL is possible for up to approximately 20 pitches, whereas unloading of the UCL to a safe level is possible for more than 100 pitches. For Pitcher ID 22, stress shielding of the UCL is not possible, whereas unloading of the UCL to a safe level is possible for more than 100 pitches.

Pitcher ID6). In fact, the relative intensity of muscular torque output required for stress shielding of the UCL exceeded 88% MVIVS in 4 of the 12 pitchers with fastball pitches, 1 with slider pitches, 0 with changeup pitches, and 1 with curveball pitches (Fig. 5), and only 8 pitchers (36.4% of all participants) were expected to have enough medial elbow muscular strength to throw fastballs or other pitch types more than 100 times without loading the UCL. These numerical results suggest that even for healthy baseball pitchers playing at a highly competitive level, valgus loading on the UCL is unavoidable during repeated pitching especially for starting pitchers whose pitch count may exceed 100 in a game and those whose pitch distribution is dominated by fastballs.

Slightly less than half the participants (n = 10) were found to have insufficient muscular varus strength to unload the UCL. The relative intensity of muscular torque output required to unload UCL was highest in fastball pitching, ranging from 101% to 157% MVIVS for these participants. Valgus loading to the UCL is inevitable every time these participants throw a fastball, even if the muscular varus torque is generated with the maximum intensity at the appropriate timing during the pitching motion (Fig. 6: Pitcher ID 22). The excess of the peak elbow varus moment during pitching over the MVIVS, which is indicative of the valgus load imposed on the UCL, joint capsule, and body articulation, reached a maximum of 33.0 N·m for fastballs, 29.0 N·m for sliders, 14.6 N·m for curveballs, and 27.0 N·m for changeups (Table 2). None of these values exceeded the elbow joint failure load of 35 N·m reported in cadaveric studies (18,19). This result is not surprising, given that no pitchers complained of elbow pain or any elbow injuries during or after data collection. Morrey and An (12) reported that the UCL, joint capsule, and bony articulation contributed 54%, 10%, and 33% of resistance, respectively, to the valgus load applied to dissected cadaveric elbow joints with all muscles removed and flexed at 90°. With all muscles intact and the flexor–pronator musculature active at the maximum level, most of the valgus load on the elbow joint should be counteracted by the muscular varus moment, with the remainder (i.e., the excess) supported by the UCL, joint capsule, and bony articulation. Applying the percent contributions reported in the cadaveric study to the excess, the valgus loading on the UCL during the pitching performances with the maximum excess (Table 2) was estimated to be 17.8 N·m for fastballs, 15.7 N·m for sliders, 7.9 N·m for curveballs, and 14.6 N·m for changeups, accounting for 16%–31% of the respective peak varus moments attained during pitching. Although the muscle contribution may vary from pitcher to pitcher, our study suggests that the medial elbow musculature serves as the primary valgus stabilizer of the elbow during pitching.

The results of this study demonstrated that, on average, the varus strength of the medial elbow musculature was as large as the peak varus moment reached during baseball pitching. In addition, the medial elbow musculature was found to generate a varus moment of 57.5 ± 9.2 N·m to resist external valgus loads, which was far greater than the varus moment that the UCL and other passive structures of elbow joint could generate before failure. These findings not only provide quantitative experimental evidence to support the accumulated knowledge obtained in controlled laboratory settings that the elbow flexor–pronator muscle group contributes substantially to elbow valgus stability (14–17,20,21,34) but also extend that knowledge to baseball pitching performance, suggesting that the medial elbow musculature can function as the primary stabilizer against the valgus loads encountered during baseball

pitching. A large valgus load applied to the pitcher's elbow during the pitching motion does not necessarily induce severe ligamentous tension in the UCL due to the synergistic function of the medial elbow musculature, but this musculature is unlikely to be able to completely unload the UCL in repeated pitching across multiple innings (Fig. 6). The contribution of the synergistic function of the musculature may partially explain why there is little firm evidence of an association between the magnitude of the resultant varus moment generated during pitching and the incidence of elbow injury (35) except for a small prospective cohort study of professional pitchers (9). The magnitude of the motion-dependent valgus torque applied to the elbow joint during the pitching motion is undoubtedly the dominant mechanical factor in elbow valgus overload injuries (1,5,6), yet it neither directly represents the valgus loading on the UCL and other static elbow stabilizers (34,36) nor by itself explains why only some pitchers sustain elbow injuries. In this study, additional variables indicative of the valgus load imposed on the elbow static stabilizers and the relative intensity of the muscular output required to completely unload the UCL were introduced to account for the pitcher's physical ability to generate synergistic muscular varus torque in assisting the UCL. For future studies, not only the peak varus moment during pitching but also the pitcher's ability to generate muscular varus moment at the appropriate time during the pitch should be examined to fully elucidate the etiology of valgus overload injuries.

There are some limitations that might have affected the results of this study and constrain the generalizability of the findings. First, the motion analysis and the strength data collection were performed with professional and collegiate baseball pitchers in Japan. The average fastball velocity (36.8 ± 2.5 m·s^{-1}) and the peak varus moment during fastball pitching presented here (58.1 ± 12.3 N·m) are comparable to the corresponding values reported from non-Japanese populations of similar levels (30–40 m·s^{-1} and 50–120 N·m) (1–10). Agreement of the numerical results obtained in the present study with the corresponding values in the literature suggests that the method and the results obtained from the combined analysis of pitching kinetics and strength are reliable and valid for generalizing the findings to the population of healthy adult pitchers playing at a highly competitive level. However, the present findings might not be applicable to other populations, such as little league pitchers and adult pitchers playing at the recreational level. Another limitation is that muscular varus strength was measured under isometric conditions, and thus, the measured torque is likely to be an underestimate of the maximum torque when the muscles involved in pitching are actually contracted. Because the elbow joint was extending at 36.0 ± 6.8 rad·s^{-1} when the peak varus moment was attained in our participants, the muscles involved should be in eccentric condition. According to an *in vivo* study of the specific tension (the maximum force development per unit physiological cross-sectional area) of elbow flexor and extensor muscles, the elbow flexors increase their strength by 18% under isokinetic eccentric condition compared with isometric condition (37). It is not known whether the elbow flexor–pronator muscles, including the flexor carpi ulnaris, flexor digitorum superficialis, and pronator teres, have similar characteristics to the elbow flexor muscles such as biceps brachii and brachialis. In future studies, the variability in the torque generating capability of a given muscle group due to the velocity dependence of muscle strength should be taken into account when muscle strength is compared with torque output during pitching.

CONCLUSIONS

This study demonstrated that 55% of the participants had sufficient isometric muscular varus strength for complete stress shielding of the UCL from valgus loading during pitching. However, even for these participants, the required relative intensity of muscular torque output was so high that pitchers would be unable to unload the UCL with submaximal effort as pitch count accumulated. These findings suggest that valgus loading is likely unavoidable in repeated baseball pitching, and thus, each pitcher is advised to build and maintain medial muscle strength and endurance appropriate for their valgus loads, expected pitch count, and pitch-type distribution in order to reduce the risk of valgus overloading to the UCL.

The authors are grateful to all the assistants and graduate students who provided technical support for the experiments. This study was partly supported by Grant-in-Aid for Scientific Research (B-19H04007) from the Japan Society for the Promotion of Science. There are no professional relationships with companies or manufacturers who will benefit from the results of this study. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of this study do not constitute an endorsement by the American College of Sports Medicine.

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