Muscle contribution to elbow joint valgus stability

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Repetitive valgus stress of the elbow can result in excessive strain or rupture of the native medial ulnar collateral ligament (MUCL). The flexor-pronator mass (FPM) may be particularly important for elbow valgus stability in overhead-throwing athletes. The aim of this study was to identify the relative contribution of each muscle of the FPM—that is, the flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), flexor carpi radialis (FCR), and pronator teres (PT)—and of the extensor-supinator mass, including the extensor carpi ulnaris (ECU), extensor digitorum communis (EDC), extensor carpi radialis longus and brevus, and brachioradialis, to elbow valgus stability at 45° and 90° of elbow flexion angles. Eight fresh-frozen elbow specimens (mean age at death, 73.75 ± 14.07 years) were tested. With the skin and subcutaneous tissue removed but all muscles left intact, each individual muscle of the FPM and extensor-supinator mass was loaded at 3 levels of force. During loading, strain on the MUCL and the kinematics of the elbow were measured simultaneously. Kinematic measurements were later repeated when the MUCL was fully cut. At 45° and 90° of elbow flexion, individual loading of the FCU, FDS, and FCR caused significant relief to the MUCL whereas the PT produced no significant change. Furthermore, of these flexor muscles, the FCU provided the greatest MUCL relief at both 45° and 90°. In contrast, loading of the ECU at 45° of elbow flexion produced a significant increase in MUCL strain. All FPM muscles caused significant elbow varus movement at both 45° and 90° when loaded individually. At 90°, the FCU created more motion than both the FCR and PT but not the FDS, and the FDS created more motion than the PT. The EDC and ECU created significant valgus movement at 45° and 90°, which became insignificant when the MUCL was transected. Our study suggested that the FCU, FDS, and FCR may function as dynamic stabilizers, with the FCU being the primary stabilizer for elbow valgus stability, incorporating with the MUCL for all tested joint configurations. Our findings also suggest that the ECU and EDC increased MUCL strain and elbow valgus movement at both 45° and 90°. (J Shoulder Elbow Surg 2007;16:795-802.)

Valgus overload to the elbow can contribute to articular cartilage damage[4] and temporary or permanent disability.[21,29] The medial ulnar collateral ligament (MUCL) of the elbow was thought to be one of the primary static restraints to valgus stress at the elbow.[19,32,33] It is commonly injured in elbow dislocations[23] and sports-related overuse injuries.[9,29] Injury to the MUCL often does not heal and may result in persistent valgus instability and permanent disability.[7,22,24] The torn ligament may subsequently require surgical reconstruction or repair to allow a return to previous levels of activity.[6,7,9,20] It is unclear what factors allow patients to return to normal activity after nonoperative treatment of the MUCL.[38]

The contributions of various static restraints, such as bony articulations and ligaments, to elbow valgus stability have been studied by several authors.[19,32,33] However, little is known about the dynamic stability of the elbow joint—that is, the role of muscle function in maintaining elbow valgus stability. The calculated stress on the MUCL during such common activities as throwing actually exceeds the load to failure of the native ligament,[13] suggesting that dynamic muscle contraction must play an important role to aid in counteracting the valgus load.[11,13]

Our null hypotheses were that (1) dynamic contraction of forearm muscles did not affect elbow dynamic valgus stability and (2) the contribution of muscle contraction to elbow valgus stability was equal among muscles from the flexor-pronator mass (FPM) and extensor-supinator mass (ESM). The purpose of this investigation was to determine the relative contributions of muscle activity to dynamic elbow stability in resisting valgus force and valgus motion. This investigation into the action of forearm muscles—that is, the flexor carpi ulnaris (FCU), flexor digitorum superficialis

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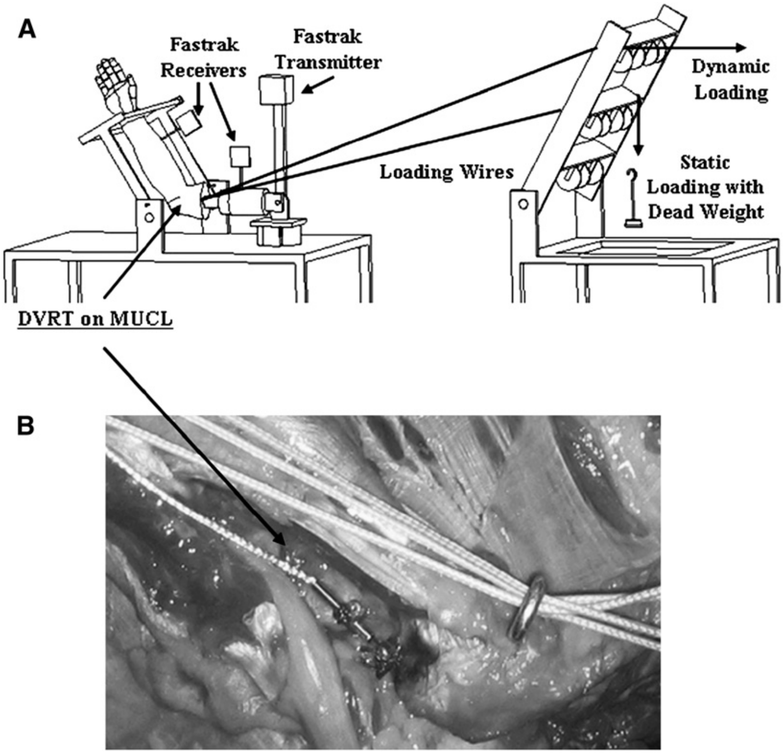

Figure 1 Experimental setup for testing effect of muscle loading on MUCL strain and elbow valgus/varus movement. **A**, Custom-designed testing device, which allowed varus-valgus and flexion-extension of forearm relative to fixed humerus. An electromagnetic tracking system (Fastrak; Polhemus) was used to measure real-time kinematics of the elbow joint. **B**, A DVRT (Microminiature DVRT; MicroStrain) with a stroke of ±1.5 mm and resolution of 0.03 mm was mounted slightly posterior to the isometric aspect of the anterior bundle of the MUCL.

(FDS), flexor carpi radialis (FCR), pronator teres (PT), extensor carpi ulnaris (ECU), extensor digitorum communis (EDC), extensor carpi radialis longus and brevus (ECR), and brachioradialis—on elbow valgus motion and strain on the anterior bundle of the MUCL aims to determine the role of the dynamic stabilizers of the elbow in response to valgus stress.

MATERIALS AND METHODS

Specimens and preparation

We tested 8 fresh-frozen elbow specimens (5 left and 3 right, 4 female and 4 male). The mean age of the donors at death was 73.75 ± 14.07 years.

The skin and subcutaneous tissues were removed down to the wrist. All muscles of the forearm were left intact. For each of the 12 muscles across the elbow joint, a thick cotton wire was sutured onto it through fiberglass mesh wrapped around the part of the muscle distal to the origin. To guide the loading direction, each of the wires was passed through an eyelet, which was placed on the muscle origin. Each wire was then directed to an individual pulley of a pulley system (Figure 1, *A*).

To allow efficient force application to the elbow joint, movement between the radius and ulna, the wrist, and the fingers was limited by use of 2 Kirschner wires (K-wires). One such K-wire was drilled through the distal portion of the radius into the ulna, thus locking the motion of the radioulnar joint and keeping the forearm at neutral pronation-supination.[2,5,8,11,34,40] Another was passed through the carpus, into the radius, to hold the wrist in neutral flexion-extension. Finally, a carbon rod was placed inside the hand with the fingers attached around it, preventing flexion-extension of the fingers.

Experimental setup

A differential variable reluctance transducer (DVRT) (Microminiature DVRT; MicroStrain, Williston, VT) with a stroke of ±1.5 mm and resolution of 0.03 mm was mounted slightly posterior to the isometric aspect of the anterior bundle of the MUCL (Figure 1, *B*). At 45° of elbow flexion, the initial length between the 2 attachment points of the DVRT was measured with a micrometer and represented the rest length. The specimen was put through several cycles of 0° to 120° of elbow flexion-extension to verify that no obstruction of the DVRT existed, as well as to confirm that the device provided consistent reading.

The specimen was mounted on a custom-designed testing device, which allowed varus-valgus and flexion-extension of the forearm relative to the fixed humerus (Figure 1, *A*). The humerus was fixed into an aluminum tube by sharp-tip screws, and the flexion-extension axis was aligned in the horizontal plane.

An electromagnetic tracking system (Fastrak; Polhemus, Colchester, VT) with 0.005 mm of position resolution and 0.025° of orientation resolution was used to measure real-time 3-dimensional translations and rotations of the elbow joint (Figure 1, *A*). One receiver was rigidly fixed to the humerus, and the other was on the forearm.

A Sensotec load cell (M31; Honeywell Sensotec, Columbus, OH) was used to measure the dynamic pulling force during individual muscle loading. In line with the load cell, a spring scale was used to allow for onsite consistency.

Experimental protocol

After the specimen was mounted on the testing apparatus, all 12 muscles were loaded with dead weights corresponding to 2% of maximum muscle force (Table I), representing the physiologic low-level muscle tone contraction.[27,28] The maximal muscle force was proportional to the mean physiologic cross-sectional area of each muscle based on data from the literature.[3,10,14,18,25–27,42] Each specimen was preconditioned through 25 times of passive flexion-extension and varus-valgus.

Two trials of passive range-of-motion (ROM) testing were conducted by slowly moving the forearm throughout 0° to 120° of elbow flexion with MUCL strain continuously recorded by the DVRT.

The specimen was tested at 2 fixed elbow flexion angles: 45° and 90°. The elbow was held in each flexion angle by differential loading of the biceps, brachialis, and triceps. At the fixed positions, each muscle from both the FPM and ESM was loaded individually at consecutive loads of approximately 22 N (approximately 5 lb), approximately 45 N (approximately 10 lb), and approximately 67 N (approximately 15 lb), respectively, for 4 seconds, with 4-second intervals between loading levels (Figure 2). During loading, strain at the center of the anterior bundle of the MUCL, the 3-dimensional movement of the elbow joint, and the loading force were simultaneously recorded. All tests were performed with an intact MUCL and later repeated with a full-thickness tear of the MUCL. Ligament strain was not recorded for the torn MUCL.

Data processing

Readings from the DVRT were used to obtain the length between the 2 barbs of the sensor—that is, the local length of the MUCL where the DVRT sensor was mounted. For each dynamic loading cycle, the offset, start of strain, and peak of strain were manually selected from the plot. For the time between these 3 points, the MUCL strain was then obtained as the percentage of length change relative to the length at the starting point of muscle loading. To characterize the contribution of each individual muscle to MUCL strain, the induced MUCL strain was normalized to 10 N of the muscle-loading force. The reason to normalize the induced MUCL strain and elbow motion to 10 N of the loading force was to avoid excessively small numbers for better interpretation of the data. A least squares linear regression was then used to fit the MUCL strain and the muscle load for each individual muscle loading; thus, the strain-load relationship was interpreted as strain over every 10 N of muscle-loading force (percent per 10 N)—that is, the slope of the linear regression. The correlation coefficient (*R*) of this linear regression was also obtained to give a measure of how well the linear fitting described the real data. Elbow kinematics was also determined for each loading cycle and similarly interpreted as the degree of rotation over 10 N of muscle-loading force (degrees per 10 N) for each individual muscle loading.

Table I Static muscle tone load for elbow muscles

Muscle	2% Maximal muscle force (N)
Biceps	7.40
Brachialis	8.74
Triceps (long head)	7.91
PT	5.23
FCU	8.77
FCR	5.04
FDS	8.66
Brachioradialis	2.27
ECR	9.57
EDC	6.80
ECU	4.91

Muscle tone was selected as 2% of maximal muscle force, proportional to the mean physiologic cross-sectional area of each muscle based on data from the literature.[3,10,14,18,25–27,42]

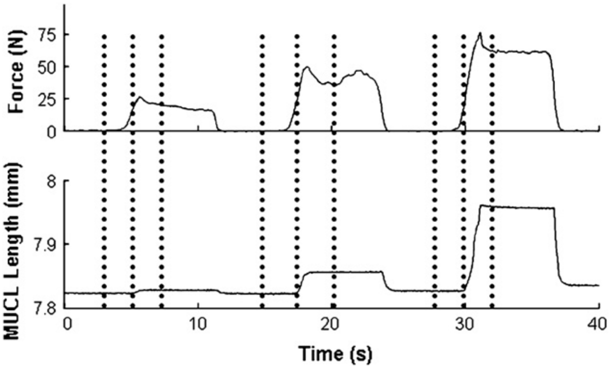

Figure 2 Typical case showing recorded data and selected data for loading cycles. *Top*, Muscle-loading force. *Bottom*, MUCL length in millimeters measured by DVRT. *Vertical dotted lines* show points of no load (offset), start, and maximum strain of each loading cycle.

Statistical analysis

For testing of hypothesis 1, strain data and valgus-varus motion obtained for each individual muscle were compared with zero by *t* test to determine whether the corresponding change in MUCL strain and valgus-varus motion induced by muscle loading was significant. For testing of hypothesis 2 on MUCL strain, a 2-way analysis of variance (ANOVA) was performed to detect the significant effects of individual muscle and elbow joint angle on MUCL strain changes. For testing of hypothesis 2 on elbow valgus-varus motion, a 3-way ANOVA was performed to detect significant effects of individual muscle, elbow joint angle, and ligament tear. Both the 2-way ANOVA and 3-way ANOVA were performed separately for the FPM and ESM. For both the 2-way and 3-way ANOVA, if any of the effects showed significance, a 1-way ANOVA was then performed to obtain the *P* values. For all statistical tests, the significant level was .050, and SAS software (version 9.0; SAS Institute, Cary, NC) was used.

RESULTS

MUCL strain during elbow ROM test

A typical ROM trial from 1 specimen is shown in Figure 3, *A*. In this specific trial, the MUCL was not tensed until about 20° of elbow flexion. From this point up to about 80° of elbow flexion, the MUCL showed an almost linear tensile response to continuous stretching as the elbow flexed more. When the elbow joint flexed more than 80°, the MUCL tensile behavior, with respect to the elbow flexion angle, went to a nonlinear stage, where less MUCL lengthening was observed as the elbow flexed further. When the elbow was extended from the flexed configuration, the stretched MUCL went through a relaxation phase with 2 consecutively distinct relaxing rates; each showed a linear pattern with a faster relaxation after the joint returned to 80° or less of elbow flexion.

The averaged MUCL strain response to elbow ROM across all 8 specimens (Figure 3, *B*) maintained a similar linear pattern throughout the elbow flexion range of 0° to 90°.

MUCL strain induced by loading individual muscle

A typical data set from a single loading trial from a specimen is shown in Figure 2. In this specific trial, 1 muscle from the ESM group was loaded for 3 cycles (top) and induced consistent MUCL lengthening (bottom). The dotted lines show the offset, start of strain, and peak of strain for each loading cycle in this trial. Several sets of such strain-load data are shown in Figure 4 for muscles from the FPM group in one loading condition for a specimen.

For the FPM group, at 45° and 90° of elbow flexion, individual loading of the FCU, FDS, and FCR caused significant relief to the MUCL (P^{Δ} in Table II, $P < .050$) whereas the PT produced no significant change ($P > .050$). Therefore, for MUCL strain data, our null hypothesis 1 was rejected for the FCU, FDS, and FCR but not for the PT. Two-way ANOVA testing showed that the relief was significantly different at the 45° and 90° elbow flexion angles, as well as among the muscles in the FPM group. Further tests on these effects showed that loading of the FCU and FDS provided significantly higher MUCL relief at 90° of elbow flexion than those at 45°. At 45° of elbow flexion, loading the FCU provided the greatest MUCL relief ($P < .001$ vs the other 3 muscles). Similar results were found at 90° of elbow flexion with regard to the FCU being the muscle that provided the greatest MUCL relief ($P < .001$ vs FCR and PT and $P < .010$ vs FDS). Our null hypothesis 2 was rejected for the FPM group for MUCL strain data.

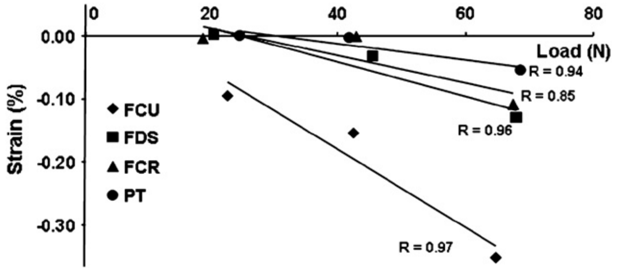

Figure 3 Typical case showing linear regression in data processing of MUCL strain induced by individual muscle loading. Linear regression for each loaded muscle and the corresponding correlation coefficient are shown. Typical data are for loading muscles of the FPM from 1 specimen.

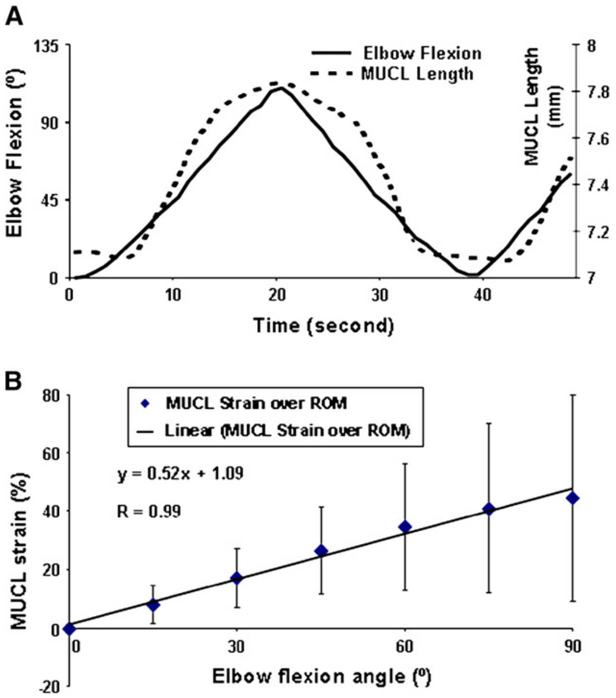

Figure 4 Typical and mean MUCL strain (percent) (mean ± SD, N = 8) over ROM of elbow flexion of 0° to 90°. **A**, Typical ROM trial showing that MUCL length varies with elbow joint flexion angle. The data are from 1 trial of 1 specimen. **B**, Averaged MUCL strain across 8 specimens in range of elbow flexion of 0° to 90° and linear regression of relationship between MUCL strain and elbow flexion angle.

For the ESM group, loading of the ECU at 45° of elbow flexion produced a significant increase in MUCL strain ($P < .050$). Loading of all other muscles in the ESM group did not induce any significant MUCL strain

Table II Mean MUCL strain changes induced by individual muscle loading

	45° Elbow flexion		90° Elbow flexion	
Muscle	**Strain (%/10 N)**	***R***	**Strain (%/10 N)**	***R***
FPM				
FCU	−0.176 ± 0.129	0.85 ± 0.16	−0.388 ± 0.295	0.88 ± 0.11
P^{Δ}	.033		.004	
P°	.042			
FDS	−0.035 ± 0.039	0.87 ± 0.13	−0.131 ± 0.086	0.84 ± 0.13
P^{Δ}	.019		.002	
P°	.010			
FCR	−0.007 ± 0.007	0.79 ± 0.28	−0.016 ± 0.019	0.76 ± 0.29
P^{Δ}	.014		.024	
P°	>.05			
PT	0.001 ± 0.040	0.81 ± 0.31	−0.003 ± 0.005	0.71 ± 0.33
P^{Δ}	>.05		>.05	
P°	—			
ESM				
EDC	0.091 ± 0.205	0.83 ± 0.11	0.043 ± 0.070	0.82 ± 0.23
P^{Δ}	>.05		>.05	
P°	—			
ECU	0.160 ± 0.201	0.95 ± 0.05	0.048 ± 0.075	0.81 ± 0.26
P^{Δ}	.029		>.05	
P°	.024			
ECR	0.003 ± 0.008	0.64 ± 0.28	0.038 ± 0.099	0.65 ± 0.27
P^{Δ}	>.05		>.05	
P°	—			
Brachioradialis	0.003 ± 0.006	0.60 ± 0.36	0.043 ± 0.079	0.80 ± 0.17
P^{Δ}	>.05		>.05	
P°	—			

Data are presented as mean ± SD. Data are normalized in the format as percentage strain changes over 10 N of muscle load and are given for an intact MUCL at 45° and 90° of elbow flexion. A positive value indicates increased tension. The significance of the MUCL strain changes (P^{Δ}) and the significance of the differences between data at these 2 angles (P°) are also reported.

R, Average correlation coefficient for linear regression of MUCL strain data for each muscle; P^{Δ}, significance as compared with zero (which is used to detect whether loading of an individual muscle significantly alters MUCL tension); P°, significant difference between corresponding data at 45° and 90° of elbow flexion (where comparison of strain data between 2 elbow angles was not performed when there was not a significant strain change at either elbow angle).

change at either 45° or 90° of elbow flexion. Therefore, for MUCL strain data, our null hypothesis 1 was only rejected for the ECU at 45° of elbow flexion.

Elbow varus-valgus motion induced by loading individual muscle

Overall, loading of the muscles in the FPM group created elbow varus movements, whereas loading those in the ESM group induced valgus movement. To be able to compare varus-valgus data from different muscles at different loading conditions, varus-valgus data were normalized to the corresponding loading force applied to each individual muscle and interpreted as degrees per 10 N (Table III).

For the FPM group, individual loading of all muscles, at 45° and 90° of elbow flexion, created significant elbow varus movements, thus rejecting hypothesis 1 on valgus-varus motion. The difference among muscles existed only in 2 testing conditions—that is, 45° with a cut MUCL and 90° with an intact MUCL. At 90° with an intact MUCL, loading the FCU produced the greatest elbow varus movement compared with the rest of the FPM muscles ($P < .050$ vs FCR, $P < .010$ vs PT, and $P =$ not significant vs FDS). Loading the FDS also induced significantly higher elbow varus movement than the PT ($P < .050$). In the condition of 45° of elbow flexion with a cut MUCL, loading the FDS caused the greatest elbow varus movement; however, this was only significantly larger than that induced by the PT ($P < .050$). Therefore, in these conditions, hypothesis 2 was rejected for valgus-varus motion.

It was also found that the elbow flexion angle affected the varus movement created by loading FPM muscles. The varus movement was always significantly higher at 45° than that at 90° for the FDS and FCR, with either an intact or a cut MUCL, and for the PT with a cut MUCL.

In addition, the MUCL condition (ie, intact or fully torn) was found to affect the elbow varus movement caused by loading FPM muscles, in that an intact

Table III Mean elbow joint varus-valgus induced by individual muscle loading

	45° Elbow flexion		90° Elbow flexion	
Muscle	**Intact MUCL (°/10 N)**	**MUCL with full-thickness tear (°/10 N)**	**Intact MUCL (°/10 N)**	**MUCL with full-thickness tear (°/10 N)**
FPM				
FCU	−0.170 ± 0.124	−0.096 ± 0.069	−0.135 ± 0.053	−0.086 ± 0.082
R	0.89 ± 0.27	0.98 ± 0.02	0.89 ± 0.21	0.94 ± 0.09
$P^{\triangle}$	.003	.003	<.001	.010
P°	>.05	>.05		
FDS	−0.151 ± 0.057	−0.108 ± 0.078	−0.116 ± 0.038	−0.065 ± 0.071
R	0.95 ± 0.04	0.97 ± 0.04	0.95 ± 0.04	0.96 ± 0.05
$P^{\triangle}$	<.001	.003	<.001	.018
P°	>.05	.017		
FCR	−0.151 ± 0.066	−0.103 ± 0.045	−0.067 ± 0.037	−0.062 ± 0.051
R	0.97 ± 0.03	0.98 ± 0.04	0.97 ± 0.03	0.86 ± 0.34
$P^{\triangle}$	<.001	<.001	.001	.005
P°	.004	.004		
PT	−0.090 ± 0.063	−0.044 ± 0.031	−0.029 ± 0.033	−0.025 ± 0.023
R	0.99 ± 0.00	0.94 ± 0.09	0.86 ± 0.16	0.75 ± 0.38
$P^{\triangle}$	.002	.002	.021	.008
P°	.046	>.05		
ESM				
EDC	0.050 ± 0.042	0.036 ± 0.055	0.031 ± 0.029	0.026 ± 0.070
R	0.98 ± 0.03	0.98 ± 0.02	0.81 ± 0.32	0.85 ± 0.26
$P^{\triangle}$	.006	>.05	.010	>.05
P°	.027	—		
ECU	0.066 ± 0.051	0.045 ± 0.093	0.055 ± 0.027	0.002 ± 0.132
R	0.99 ± 0.01	0.99 ± 0.02	0.95 ± 0.05	0.91 ± 0.15
$P^{\triangle}$	.004	>.05	<.001	>.05
P°	>.05	—		
ECR	0.020 ± 0.026	0.018 ± 0.022	0.006 ± 0.027	−0.004 ± 0.022
R	0.98 ± 0.02	0.81 ± 0.30	0.84 ± 0.27	0.87 ± 0.21
$P^{\triangle}$	.037	.026	>.05	>.05
P°	>.05	.039		
Brachioradialis	0.008 ± 0.065	0.012 ± 0.045	−0.007 ± 0.030	0.025 ± 0.066
R	0.94 ± 0.07	0.83 ± 0.20	0.82 ± 0.22	0.98 ± 0.03
$P^{\triangle}$	>.05	>.05	>.05	>.05
P°	—	—		

Data are presented as mean ± SD. Data are normalized in the format as varus-valgus motion created by 10 N of muscle load. A positive value indicates valgus. Data are given for intact MUCL and MUCL with full-thickness tear at 45° and 90° of elbow flexion. The significance of elbow varus-valgus motion ($P^{\triangle}$) and the significance of the differences between data at these 2 angles (P°) are also reported for those conditions when significant varus-valgus was observed.

R, Average correlation coefficient for linear regression of elbow varus-valgus induced by loading each individual muscle; $P^{\triangle}$, significant change as compared with zero (which is used to examine whether loading of an individual muscle generates significant joint motion); P°, significant difference between corresponding data at 45° and 90° of elbow flexion (where comparison of motion data between 2 elbow angles was not performed when there was no significant varus-valgus movement induced at either elbow angle).

MUCL allowed the FPM muscles to create more elbow varus movement ($P < .010$).

For the ESM group, loading of the EDC and ECU created significant elbow valgus movement at 45° and 90° of elbow flexion only when the MUCL was intact. Loading of the ECR only created significant elbow valgus movement at 45° with both an intact and a fully torn MUCL. Therefore, for elbow valgus-varus motion, hypothesis 1 was rejected for the EDC and ECU when the MUCL was intact and for the ECR only at 45° of elbow flexion. There was no other significant effect for the elbow varus-valgus movement induced by ESM muscles.

DISCUSSION

Many biomechanical studies have established that the anterior portion of the MUCL acts as the elbow's main stabilizer to valgus stress.[8,15,31–33,37,39] Because the ultimate torque strength was reported to be 34 Nm,[12] whereas up to 120 Nm of elbow valgus torque could be experienced in overhead-throwing athletes,[41] it was believed that some of the stress was shared by the overlying FPM.[13,41] It was on this basis that progress has been made in the development of studies focused on the FPM's ability to generate force vectors similar to the static reaction force vector of the MUCL, thus aiding the MUCL during extreme valgus loads.* At both 45° and 90°, our results showed that the FCU provided the most relief of the MUCL strain compared with the other FPM muscles. The FCU also generated the greatest varus rotation whereas the PT had the least, in agreement with the study of valgus stability of Park and Ahmad.[34] Because it is believed that the FPM adds dynamic valgus stability, one would assume that FPM activity might increase, or at least stay the same, to compensate for an MUCL deficiency, preventing further injury. However, electromyographic studies of the elbow showed that there was an increase in ESM activation and decrease in FPM activation in injured pitchers during the acceleration phase.[16,17] Furthermore, our test showed that when the ESM was loaded and, more specifically, the ECU and EDC, valgus movements and increased MUCL strain were recorded, thus amplifying this paradox. Hamilton et al[17] and Glousman et al[16] both discussed how it remains unclear whether the FPM muscles had impaired firing before injury. This might explain the different FPM activities between the injured and uninjured pitchers, in that the MUCL injury might have occurred from inadequate protection given by the FPM.

During the elbow ROM test, it was shown that the anterior bundle of the MUCL responded at about 20° of elbow flexion and continued throughout elbow flexion. There was a linear part of the MUCL strain with respect to the elbow flexion angle before reaching 75° to 80° of flexion. Thereafter, the MUCL strain responded less to further flexion (Figure 3). This finding is consistent with previously reported data indicating that the anterior bundle of the MUCL developed strain at about 30° elbow flexion[36] and tensed less after 90° of elbow flexion.[8]

This study found that action of the FCU, FDS, or FCR significantly decreases MUCL strain at both flexion angles, and significantly greater MUCL relief was seen at 90° of elbow flexion for the FCU and FDS. The increased MUCL relief from the FPM muscles at 90° of elbow flexion could be a result of the anterior band of the MUCL being more tense (loaded) at 90°, as seen in the ROM data (Figure 3). On the contrary, the ESM muscles produced the opposite effect on the MUCL strain at both flexion angles. All ESM muscles were found to be tensing the MUCL, and a greater such tensing effect was seen at 45° of elbow flexion (only significant for ECU). Therefore, our results suggested that, in a more flexed elbow, loading of the FPM muscle creates more MUCL strain relief, which may prevent the MUCL from being excessively elongated into injury.

The contribution to MUCL relief and tension from dynamic loading of the FPM and ESM muscles can also be corroborated by the data from elbow varus-valgus motion induced by loading these muscles (Table III). Our data show that all FPM muscles produced significant varus motion whereas all ESM muscles did the opposite. It is suggested that FPM muscles release the MUCL strain by generating varus motion, which effectively reduces the MUCL load. The FCU and ECU both provided the most varus and valgus, respectively, when the MUCL was intact. Our data also show that despite a larger varus motion seen at 45° than at 90°, there was more strain decrease at 90°. As mentioned previously, the MUCL was more tensed at 90° than at 45° of elbow flexion, thus providing additional support to joint stability and limiting valgus-varus motion.

Onsite observation during the removal of the MUCL revealed excessive laxity on the medial side of the joint. As a result of this laxity, the slightly lower varus movements experienced by the limb could be a result of losing architecture, possibly affecting the pivot point and resultant force vector of certain muscles. Lacking an enclosed medial capsule might cause more compression and shear, resulting in less varus movement.

In the torn MUCL condition of our study, lacking of the medial static restraint should allow more valgus movement to occur from dynamic extensor loading. However, no greater valgus movement was seen during this condition. It is our belief that whether the MUCL was intact or not, static loading of the flexors provided enough balance to the extensors both before and after the cut, preventing excessive valgus motion.

There are limitations in our study that must be accounted for. As mentioned by Park and Ahmad,[34] finding an internal control of each specimen for statistical analysis would aid in decreasing SD and increasing relative values. Although specimens will have anatomic discrepancies, ligament strain will consistently vary. It was observed in our experiment that female specimens exhibited more flexibility of the elbow capsule when manual varus-valgus loads were applied to the forearm.

Similar to Park and Ahmad[34] and Morrey et al,[33] we used low-level loads to establish relative movement of the limb. Increasing loads, with care taken not to damage the specimen, might provide more significant changes of the data, allowing more accurate evaluation.

This study collected data on MUCL strain and elbow kinematics during elbow joint passive movement and dynamic individual muscle loading. More importantly, data regarding the MUCL strain, along with the corresponding dynamic individual muscle loading, revealed the specific contribution of each individual

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*References 1, 8, 9, 11, 15–17, 19, 24, 30, 31, 33–35.

muscle in dynamically assisting the static stabilizing task of the MUCL for the elbow joint. This protocol of dynamic evaluation for the elbow joint may open up more possibilities with regard to future research of dynamic stability in the elbow joint.

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REFERENCES

1. Alcid JG, Ahmad CS, Lee TQ. Elbow anatomy and structural biomechanics. Clin Sports Med 2004;23:503-17, vii.
2. An K-N, Morrey BF, Chao EY. The effect of partial removal of proximal ulna on elbow constraint. Clin Orthop Relat Res 1986:270-9.
3. An KN, Hui FC, Morrey BF, Linscheid RL, Chao EY. Muscles across the elbow joint: a biomechanical analysis. J Biomech 1981;14: 659-69.
4. Andrews JR. Bony injuries about the elbow in the throwing athlete. Instr Course Lect 1985;34:323-31.
5. Andrews JR, Heggland EJH, Fleisig GS, Zheng N. Relationship of ulnar collateral ligament strain to amount of medial olecranon. Am J Sports Med 2001;29:716-21.
6. Azar FM, Andrews JR, Wilk KE, Groh D. Operative treatment of ulnar collateral ligament injuries of the elbow in athletes. Am J Sports Med 2000;28:16-23.
7. Bennett JB, Green MS, Tullos HS. Surgical management of chronic medial elbow instability. Clin Orthop Relat Res 1992:62-8.
8. Callaway GH, Field LD, Deng X-H, Torzilli PA, O'Brien SJ, Altchek DW, et al. Biomechanical evaluation of the medial collateral ligament of the elbow. J Bone Joint Surg Am 1997;79: 1223-31.
9. Conway JE, Jobe FW, Glousman RE. Medial instability of the elbow in throwing athletes. J Bone Joint Surg Am 1992;74:67-83.
10. Cutts A, Alexander RM, Ker RF. Ratios of cross-sectional areas of muscles and their tendons in a healthy human forearm. J Anat 1991;176:133-7.
11. 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;23:245-50.
12. Dillman C, Smutz P, Werner S. Valgus extension overload in baseball pitching [abstract]. Med Sci Sports Exerc 1991;23:S135.
13. Fleisig GS, Andrews JR, Dillman CJ, Escamilla R. Kinetics of baseball pitching with implications about injury mechanisms. Am J Sports Med 1995;23:233-9.
14. Freund J, Takala E-P. A dynamic model of the forearm including fatigue. J Biomech 2001;34:597-605.
15. Fuss FK. The ulnar collateral ligament of the human elbow joint. Anatomy, function and biomechanics. J Anat 1991;175:203-12.
16. Glousman RE, Barron J, Jobe FW, Perry J, Pink M. An electromyographic analysis of the elbow in normal and injured pitchers with medial collateral ligament insufficiency. Am J Sports Med 1992; 20:311-7.
17. Hamilton CD, Glousman RE, Jobe FW, Brault J, Pink M, Perry J. Dynamic stability of the elbow. J Shoulder Elbow Surg 1996;5: 347-54.
18. Herman AM, Delp SL. Moment arm and force-generating capacity of the extensor carpi ulnaris after transfer to the extensor carpi radialis brevis. J Hand Surg [Am] 1999;24:1083-90.
19. Hotchkiss RN, Weiland AJ. Valgus stability of the elbow. J Orthop Res 1987;5:372-7.
20. Hyman J, Breazeale NM, Altchek DW. Valgus instability of the elbow in athletes. Clin Sports Med 2001;20:25-45.
21. Jobe CM. Gross anatomy of the shoulder. In: Rockwood J, Charles A, Matsen F III, editors. The shoulder. Philadelphia: Saunders; 1990. p. 34-97.
22. Jobe FW, Stark H, Lombardo SJ. Reconstruction of the ulnar collateral ligament in athletes. J Bone Joint Surg Am 1986;68: 1158-63.
23. Josefsson PO, Johnell O, Wendeberg B. Ligamentous injuries in dislocations of the elbow joint. Clin Orthop Relat Res 1987:221-5.
24. Kuroda S, Sakamaki K. Ulnar collateral ligament tears of the elbow joint. Clin Orthop Relat Res 1986:266-71.
25. Lemay MA, Crago PE. A dynamic model for simulating movements of the elbow, forearm, and wrist. J Biomech 1996;29:1319-30.
26. Lieber RL, Fazeli BM, Botte MJ. Architecture of selected wrist flexor and extensor muscles. J Hand Surg [Am] 1990;15:244-50.
27. Makhsous M. Improvements, validation, and adaptation of a shoulder model [PhD thesis]. Gothenburg, Sweden: Polymetric Department, Chalmers University of Technology; 1999.
28. Makhsous M, Lin AF, Zhang LQ. Multi-axis passive and active stiffnesses of the glenohumeral joint. Clin Biomech (Bristol, Avon) 2004;19:107-15.
29. Miller CD, Savoie FH III. Valgus extension injuries of the elbow in the throwing athlete. J Am Acad Orthop Surg 1994;2:261-9.
30. Morrey BF. Applied anatomy and biomechanics of the elbow joint. Instr Course Lect 1986;35:59-68.
31. Morrey BF, An K-N. Functional anatomy of the ligaments of the elbow. Clin Orthop Relat Res 1985:84-90.
32. Morrey BF, An K-N. Articular and ligamentous contributions to the stability of the elbow joint. Am J Sports Med 1983;11:315-9.
33. Morrey BF, Tanaka S, An K-N. Valgus stability of the elbow joint: a definition of primary and secondary constraints. Clin Orthop Relat Res 1991:187-95.
34. Park MC, Ahmad CS. Dynamic contributions of the flexor-pronator mass to elbow valgus stability. J Bone Joint Surg Am 2004;86: 2268-74.
35. Peng Q, Schafer D, Hsu J, Koh J, Zhang L-Q. Mechanical actions of individual muscles at the human elbow joint and their roles in protecting/unloading the ulnar collateral ligament. Conf Proc IEEE Eng Med Biol Soc 2004;7:4704-5.
36. Pribyl CR, Hurley DK, Wascher DC, McNally TP, Firoozbakhsh K, Weiser MW. Elbow ligament strain under valgus load: a biomechanical study. Orthopedics 1999;22:607-12.
37. Regan WD, Korinek SL, Morrey BF, An K-N. Biomechanical study of ligaments around the elbow joint. Clin Orthop Relat Res 1991:170-9.
38. Rettig AC, Sherrill C, Snead DS, Mendler JC, Mielings P. Nonoperative treatment of ulnar collateral ligament injuries in throwing athletes. Am J Sports Med 2001;29:15-7.
39. Schwab G, Bennett JB, Woods G, Tullos HS. Biomechanics of elbow instability: the role of the medial collateral ligament. Clin Orthop Relat Res 1980:42-52.
40. Sojbjerg JO, Ovesen J, Nielsen S. Experimental elbow instability after transection of the medial collateral ligament. Clin Orthop Relat Res 1987:186-90.
41. Werner S, Fleisig GS, Dillman C, Andrews JR. Biomechanics of the elbow during baseball pitching. J Orthop Sports Phys Ther 1993; 17:274-8.
42. Werner SL, Murray TA, Hawkins RJ, Gill TJ. Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. J Shoulder Elbow Surg 2002;11:151-5.