Dynamic Contributions of the Flexor-Pronator Mass to Elbow Valgus Stability

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Dynamic Contributions of the Flexor-Pronator Mass to Elbow Valgus Stability

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Background: Previous studies have indicated that the demands placed on the medial ulnar collateral ligament of the elbow when it is subjected to valgus torque during throwing exceed its failure strength, which suggests the necessary dynamic contribution of muscle forces. We hypothesized that the flexor-pronator mass assists the medial ulnar collateral ligament in stabilizing the elbow against valgus torque.

Methods: Six cadaveric elbows were tested at 30° and 90° of flexion with no other constraints to motion. A full medial ulnar collateral ligament tear was simulated in each elbow. Muscle forces were simulated on the basis of the centroids and physiological cross-sectional areas of individual muscles. The biceps, brachialis, and triceps were simulated during flexor carpi ulnaris, flexor digitorum superficialis, flexor digitorum superficialis and flexor carpi ulnaris, and pronator teres-loading conditions. Kinematic data were obtained at each flexion angle with use of a three-dimensional digitizer.

Results: Release of the medial ulnar collateral ligament caused a significant increase in valgus instability of 5.9° ± 2.4° at 30° of elbow flexion and of 4.8° ± 2.0° at 90° of elbow flexion ($p < 0.05$). The differences in valgus angulation between each muscle-simulation condition and the medial ulnar collateral ligament-intact condition were significantly different from each other ($p < 0.05$), except for the difference between the flexor carpi ulnaris contraction condition and the flexor digitorum superficialis-flexor carpi ulnaris co-contraction condition. This co-contraction provided the most correction of the valgus angle in comparison with the intact condition at both 30° and 90° of elbow flexion (1.1° ± 1.8° and 0.38° ± 2.3°, respectively). Simulation of the flexor carpi ulnaris alone provided the greatest reduction of the valgus angle among all individual flexor-pronator mass muscles tested ($p < 0.05$), whereas simulation of the pronator teres alone provided the least reduction of the valgus angle ($p < 0.05$).

Conclusions: The flexor-pronator mass dynamically stabilizes the elbow against valgus torque. The flexor carpi ulnaris is the primary stabilizer, and the flexor digitorum superficialis is a secondary stabilizer. The pronator teres provides the least dynamic stability.

Clinical Relevance: The flexor-pronator mass is capable of contributing valgus stability to the elbow. When considering injury prevention, surgical techniques, and rehabilitation in throwing athletes, the physician should give particular attention to optimizing the function of the flexor carpi ulnaris and flexor digitorum superficialis.

Numerous studies have shown that the medial ulnar collateral ligament of the elbow is the primary static stabilizer to valgus stress[1-4]. This structure is particularly important in overhead throwing athletes, who place tremendous repetitive valgus forces across the elbow during the late cocking and acceleration phases of throwing. In baseball pitchers, these valgus forces have been estimated to be 120 Nm[5]. These repetitive forces may lead to microtrauma and failure of the medial ulnar collateral ligament over time[2,4,6]. Werner et al.[5] estimated that the tensile forces that are resisted by both the dynamic and static stabilizers of the medial part of the elbow are 290 N. Fleisig et al.[7] estimated that the demand on the medial ulnar collateral ligament that is necessary to resist valgus moments during pitching is 35 Nm. Laboratory studies have demonstrated that these demands approach and may exceed the failure strength of the medial ulnar collateral ligament[8,9]. Ahmad et al.[9] reported that 34 Nm of valgus torque caused failure of the medial ulnar collateral ligament in cadaveric specimens from young donors. In another laboratory study, Regan et al.[10] observed that failure of the anterior bundle of the medial ulnar collateral ligament occurred at a load of 261 N. These discrepancies between the estimated valgus load and torque requirements for throwing and actual failure strength suggest that other sources, in addition to the medial ulnar collateral ligament, may contribute to valgus stability.

Although the role of dynamic muscle contributions to shoulder stability has been well studied with use of cadaveric models[11-13], such investigations for the elbow have been lacking. To our knowledge, Morrey et al.[14] were the first to examine the role of dynamic muscle contributions to valgus stability of the elbow by simulating the biceps, brachialis, and triceps muscles in a cadaveric model. Davidson et al.[15], in a cadaveric study, suggested that the flexor carpi ulnaris contributes to dynamic valgus stability of the elbow because of its optimal position in line with the medial ulnar collateral ligament. Clinical electromyographic studies have shown that pitchers with symptomatic valgus instability have decreased flexor-pronator mass activity when pitching, which also suggests the role of a dynamic muscle contribution to elbow stability[16,17]. An et al.[18], in a biomechanical analysis of the functional anatomy of the elbow, theoretically predicted a role for the flexor-pronator mass as a valgus stabilizer. While these studies have suggested the dynamic contribution of the flexor-pronator mass to valgus stability of the elbow, no study has directly confirmed this dynamic contribution.

We hypothesized that the flexor-pronator mass dynamically assists the medial ulnar collateral ligament in stabilizing the elbow against valgus torque, with the flexor carpi ulnaris being the primary dynamic stabilizer.

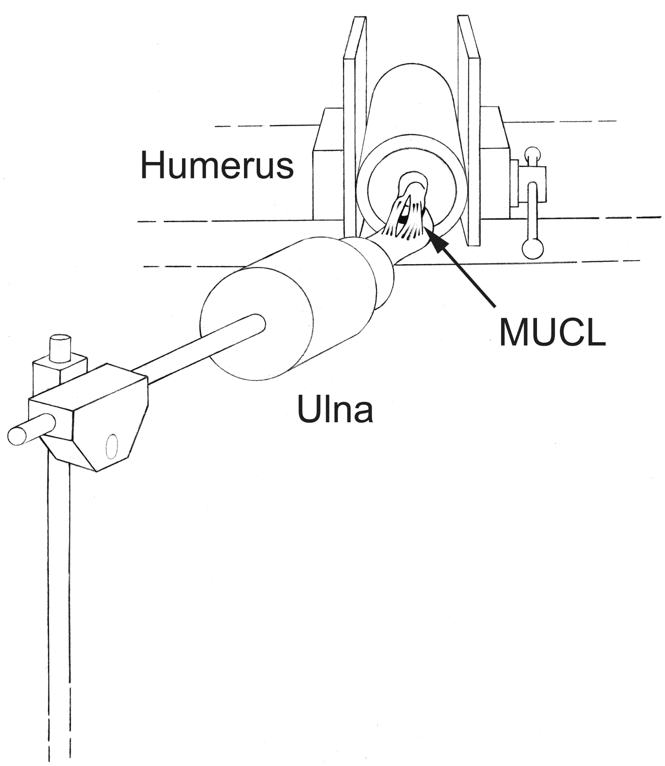

Fig. 1
Illustration depicting the experimental testing apparatus, with the elbow oriented in the horizontal plane (with the medial side superior). The testing apparatus rigidly fixed the humerus and allowed elbow flexion of 30° and 90°, with no other constraints to motion MUCL = medial ulnar collateral ligament.

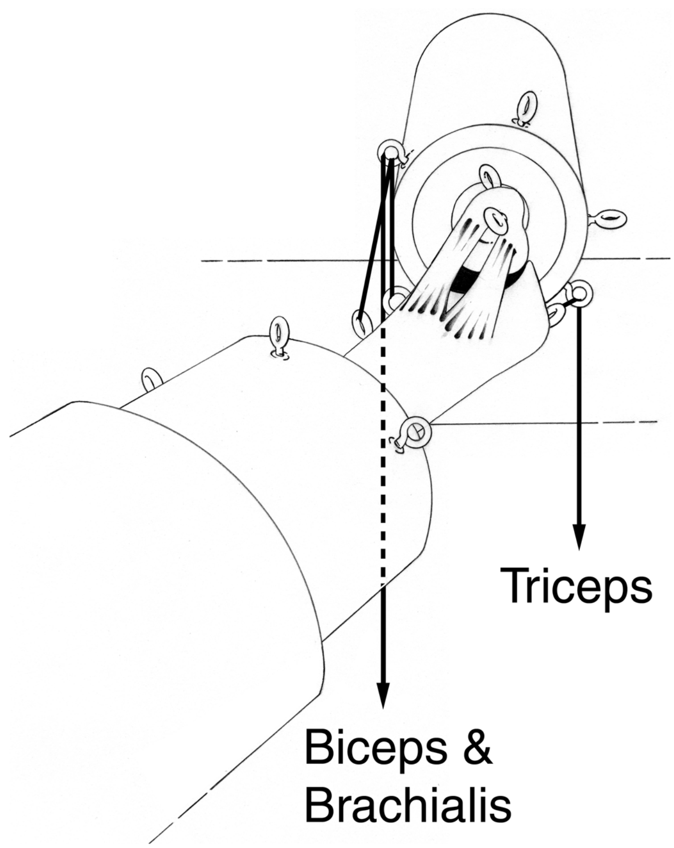

Fig. 2
Illustration depicting the eyelets with nylon cords that were used to simulate the muscle activity of the biceps, brachialis, and triceps.

Materials and Methods

Six fresh-frozen cadaveric elbow specimens from adults (one woman and five men) were dissected free of all soft tissues except for the capsule, ligaments, and muscle tissue overlying the lateral collateral ligament complex. Three specimens were from the right side, and three were from the left. The ages of the donors at the time of death were not available. Visual inspection revealed no articular degenerative changes.

The humerus, radius, and ulna of each specimen were osteotomized 14 cm from the joint line and were rigidly fixed within polyvinylchloride pipe with plaster. The radius and ulna were fixed in neutral rotation, as in other studies[3,15,19-21]. The elbows were placed in a testing apparatus that rigidly fixed the humerus and allowed elbow flexion of 30° and 90° with no other constraints to motion (Fig. 1). A gravity valgus position was used by placing the humerus horizontal to the floor, with the radius inferior and the ulna superior[14]. A smooth steel rod was attached to the polyvinylchloride pipe that was fixed to the forearm; the steel rod-holding apparatus was 27 cm long and weighed 3.9 N. A positioning device held

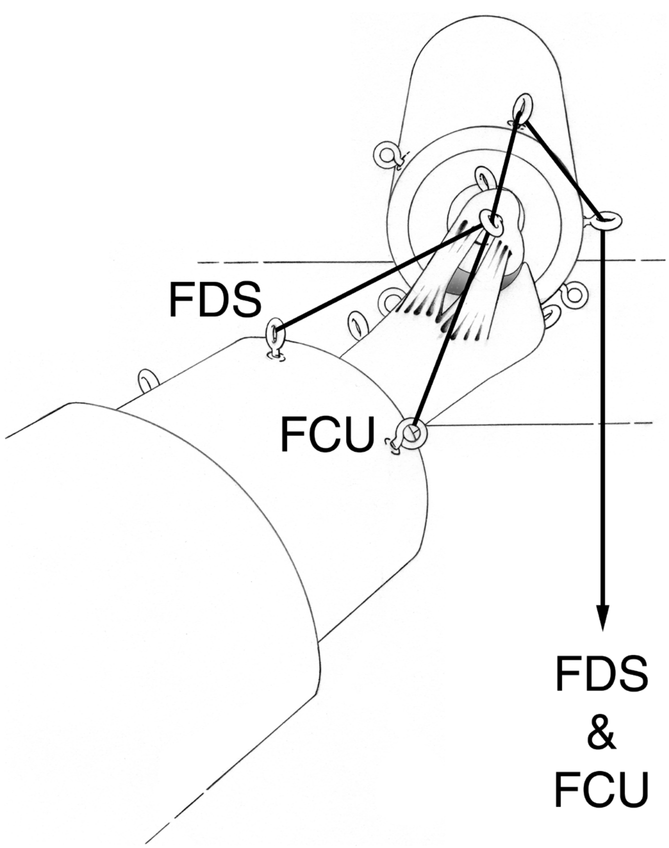

Fig. 3

Illustration depicting the eyelets with nylon cords that were used to simulate the muscle activity of the flexor digitorum superficialis (FDS) and flexor carpi ulnaris (FCU).

the steel rod at the desired flexion angles. The polyvinylchloride pipe-steel rod assembly created a 1.25-Nm moment across the elbow, which was similar to the moment of 1.5 Nm described by Sojbjerg et al.[3].

Eyelet screws were placed in line with the flexor carpi ulnaris, flexor digitorum superficialis, pronator teres, biceps, brachialis, and triceps at the muscle origins and muscle belly centroids. Placement of the eyelets was performed by direct visual inspection of the muscles as described by An et al.[18]. Loading was achieved by attaching free weights to monofilament nylon cords that were passed through the eyelets (Figs. 2, 3, and 4), similar to the method described by Morrey and colleagues in previously reported cadaveric elbow studies[14,22,23].

Testing was performed with a medial ulnar collateral ligament-intact condition and with a medial ulnar collateral ligament-insufficient condition. The latter condition was achieved by resecting the deep fibers of the anterior bundle from the site of humeral attachment. The majority (68%) of complete medial ulnar collateral ligament tears in throwing athletes have been reported to occur proximally[24]. After resection, at least 3 mm of joint-space opening was created at 30° of elbow flexion in all specimens.

An et al.[18] previously reported the physiological cross-sectional areas of the muscles that were simulated in the present study. The cross-sectional areas provide a measure of each individual muscle's force-generating potential. The relative potentials of simulated muscles can be calculated with use of the ratios of the cross-sectional areas. The ratios can be used to calculate loading simulations for co-contractions. This load-magnitude selection method is consistent with those described in previously published studies on the upper extremity in which co-contractions were simulated[11,25,26]. For all of the loads in the current study, lead beads were placed in containers that were attached to the nylon cords representing each muscle. The lead beads were titrated to the amounts necessary to match the calculated load ratios.

All muscle simulations were performed on medial ulnar collateral ligament-insufficient elbows. The containers with lead beads were used to create loads of 10.0 N, 2.45 N, and 3.72 N for the triceps, biceps, and brachialis, respectively. These elbow flexor and extensor muscle forces cause ulnohumeral joint compression. This ulnohumeral compression is in contrast to the varus moments that are caused by the flexor carpi ulnaris, flexor digitorum superficialis, and pronator teres, which were simulated with 15.0-N loads in order to compare their relative contributions to valgus stability of the elbow. For one phase of the experiment, the flexor digitorum superficialis

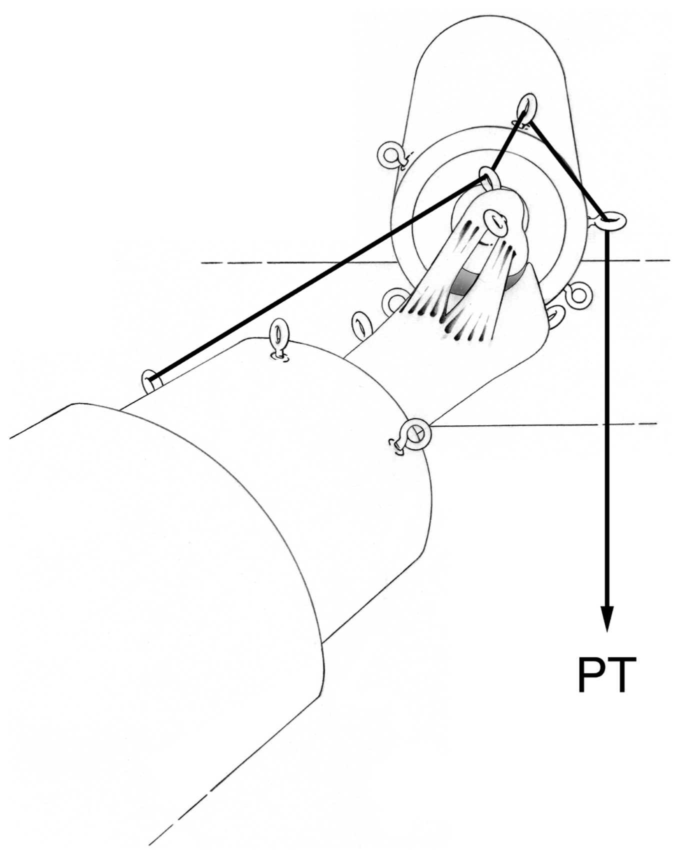

Fig. 4

Illustration depicting the eyelets with nylon cords that were used to simulate the muscle activity of the pronator teres (PT).

and flexor carpi ulnaris were loaded together. On the basis of proportions derived from data on the physiological cross-sectional areas of the muscles[18], it was determined that, for 15.0 N of flexor digitorum superficialis contraction, 7.87 N of flexor carpi ulnaris co-contraction would be required.

For all elbow conditions, three points in space along the forearm, relative to three points along the humerus, were digitized in order to obtain kinematic data with use of a three-dimensional coordinate measuring machine (MicroScribe; Immersion, San Jose, California). The valgus angle was calculated from the digitized points at both 30° and 90° of elbow flexion under several conditions: (1) no loading of the medial ulnar collateral ligament-intact elbow, (2) no loading of the medial ulnar collateral ligament-insufficient elbow, (3) co-contraction of the biceps, brachialis, and triceps, (4) contraction of the flexor carpi ulnaris, (5) co-contraction of the flexor digitorum superficialis and flexor carpi ulnaris, (6) contraction of the flexor digitorum superficialis, and (7) contraction of the pronator teres. For each of the flexor-pronator mass conditions tested, the biceps, brachialis, and triceps were simulated concomitantly. After the medial ulnar collateral ligament was resected, the order of testing was performed randomly.

Statistical Methods

All conditions were tested in the same specimen; thus, statistical analysis was performed with use of a two-factor analysis of variance with repeated measures on both factors. The two factors were the muscle-loading condition (i.e., flexor carpi ulnaris, flexor digitorum superficialis-flexor carpi ulnaris, flexor digitorum superficialis, and pronator teres activities performed in association with concomitant biceps, brachialis, and triceps activities) and the elbow flexion angle (30° and 90°). The valgus angle was considered to be the dependent variable. When an elbow condition was found to be significant with use of a two-factor analysis of variance ($p < 0.05$), a Student-Newman-Keuls multiple-comparisons test was used to detect significant differences between the muscle-loading conditions. Each condition represents a difference in the valgus angle relative to that in the medial ulnar collateral ligament-intact elbow.

Results

The valgus angle was measured with the medial ulnar collateral ligament-intact condition serving as an internal control for each specimen; Figures 5-A and 5-B show the differences in valgus angles relative to this condition. Release of the medial ulnar collateral ligament caused 5.9° ± 2.4° of valgus instability at 30° of elbow flexion and 4.8° ± 2.0° of valgus instability at 90° of elbow flexion (as shown by the bar labeled "No load" in Figs. 5-A and 5-B).

When the differences in the valgus angle between each

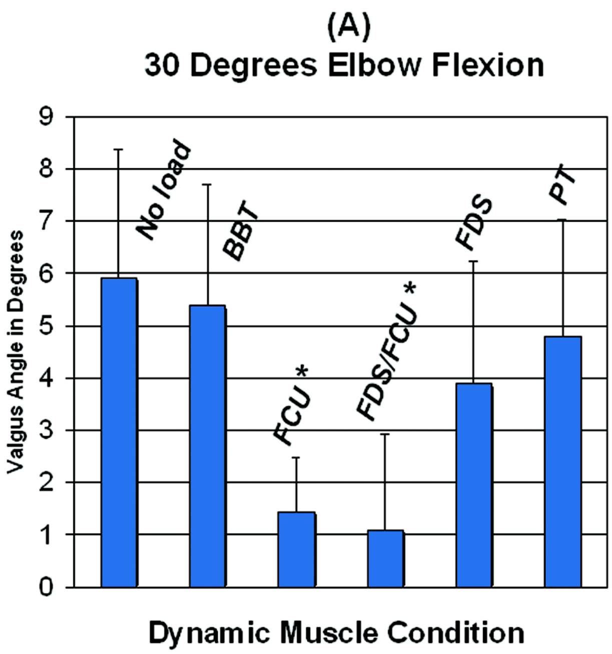

Fig. 5-A

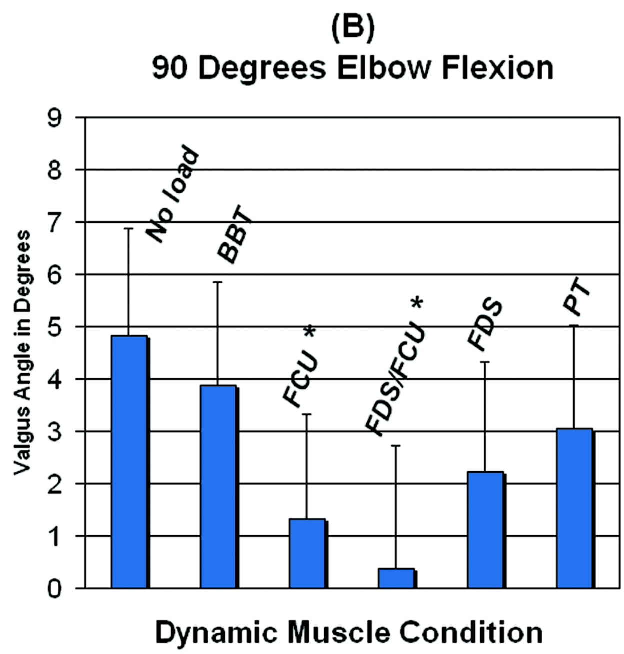

Fig. 5-B

Figs. 5-A and 5-B Illustration showing the means and standard deviations for the valgus angles as differences from the medial ulnar collateral ligament-intact condition during the experimental simulations at 30° (Fig. 5-A) and 90° (Fig. 5-B) of elbow flexion. The medial ulnar collateral ligament was insufficient during all simulations, which included (1) no loading of any muscles (No load), (2) biceps-brachialis-triceps (BBT) co-contraction, (3) flexor carpi ulnaris (FCU) contraction, (4) flexor digitorum superficialis-flexor carpi ulnaris (FDS/FCU) co-contraction, (5) flexor digitorum superficialis (FDS) contraction, and (6) pronator teres (PT) contraction. All conditions (except for the flexor carpi ulnaris contraction and the flexor digitorum superficialis-flexor carpi ulnaris co-contraction) were significantly different from each other at both flexion angles. For all flexor-pronator mass simulations, the biceps, brachialis, and triceps were concurrently simulated. * = no significant difference.

muscle-loading simulation and the medial ulnar collateral ligament-intact condition were compared at both 30° and 90° of elbow flexion, the *differences for each simulation* were significantly different from each other ($p < 0.05$) except when the flexor carpi ulnaris contraction was compared with the flexor digitorum superficialis-flexor carpi ulnaris co-contraction (Figs. 5-A and 5-B). Simulation of the flexor carpi ulnaris muscle alone reduced the valgus angle more than did simulation of the flexor digitorum superficialis alone ($p < 0.05$). The flexor digitorum superficialis-flexor carpi ulnaris co-contraction provided the most correction of the valgus angle compared with the medial ulnar collateral ligament-intact condition at both 30° and 90° of elbow flexion (1.1° ± 1.8° and 0.38° ± 2.3°, respectively); these results were significantly different from those following simulation of the flexor digitorum superficialis alone at both flexion angles ($p < 0.05$). Simulation of the pronator teres alone reduced the valgus angle ($p < 0.05$) but was the least effective of the flexor-pronator muscle mass simulations tested. Simulation of the flexor carpi ulnaris alone provided the most reduction of the valgus angle among all of the individual muscles that were tested, with reduction of the valgus angle to 1.4° ± 1.0° at 30° of elbow flexion and to 1.3° ± 2.0° at 90° of elbow flexion.

Discussion

Based on the results of numerous studies that have revealed discrepancies between the static failure strength of the medial ulnar collateral ligament and the estimated demands that are placed on the medial part of the elbow during pitching[5,7-10], the hypothesis that the flexor-pronator mass contributes to valgus stability of the elbow was tested. Our results demonstrated that simulated contraction of the flexor carpi ulnaris, at both 30° and 90° of elbow flexion, provided the greatest stability to the medial ulnar collateral ligament-insufficient elbow when compared with the loading of other individual flexor-pronator mass muscles. Simulated co-contraction of the flexor digitorum superficialis and flexor carpi ulnaris provided comparable dynamic stability to simulated contraction of the flexor carpi ulnaris alone. These findings are consistent with those reported by Davidson et al.[15], who showed that the flexor carpi ulnaris is optimally positioned to provide support directly in line with the medial ulnar collateral ligament, with the flexor digitorum superficialis in a slightly less advantageous location.

In the study by Glousman et al.[17], electromyographic analysis showed that the pronator teres had decreased activity in pitchers with medial ulnar collateral ligament insufficiency, suggesting that this asynchronous muscle action may predispose the elbow joint to further injury. In the study by Hamilton et al.[16], electromyographic analysis showed decreased activity in the flexor-pronator group in pitchers with valgus instability; the flexor carpi ulnaris had decreased activity during all pitching phases in athletes with medial ulnar collateral ligament injury compared with those with normal elbows, whereas the flexor digitorum superficialis showed no change between the groups. On the basis of these electromyographic findings, the authors concluded that the flexor-pronator mass does not provide dynamic stability in the medial ulnar collateral ligament-insufficient elbow. They added, however, that it remains unclear whether these muscles have impaired firing before medial ulnar collateral ligament injury. Another theory, not directly stated in their study, is that flexor-pronator mass injury occurs before or concurrently with medial ulnar collateral ligament injury. Therefore, these electromyographic results[16,17] suggest that valgus instability may be more symptomatic when dynamic muscle forces are not optimally functioning. Our in vitro results, which suggest that the flexor carpi ulnaris is a primary dynamic stabilizer of the medial part of the elbow, are consistent with this theory.

Numerous studies have shown that a certain percentage of patients with a medial ulnar collateral ligament tear have a flexor-pronator mass injury[4,27-29]. Conway et al.[4] reported that a rupture in the substance of the flexor-pronator mass near its origin on the medial epicondyle was observed at the time of operative treatment in nine (13%) of seventy elbows in pitchers with medial ulnar collateral ligament failure. These studies highlight the possibility of concomitant injury to the flexor-pronator mass in pitchers with valgus instability. The fibers of the flexor carpi ulnaris are intimately attached to the medial ulnar collateral ligament and therefore flexor carpi ulnaris injury in the setting of medial ulnar collateral ligament insufficiency may be obligatory, at least to a certain degree, according to these studies[4,27-29]. Our finding that the flexor carpi ulnaris is a primary dynamic stabilizer suggests that the degree of flexor carpi ulnaris dysfunction may correlate clinically with symptoms of instability and pain in athletes such as pitchers who repetitively exert an overhead throwing motion.

The importance of the flexor-pronator mass has been highlighted by investigators who have advocated limiting dissection of the flexor-pronator mass during reconstruction of the medial ulnar collateral ligament[9,30,31]. Smith et al.[30] defined a safe zone, designed to minimize nerve injury, through the posterior one-third of the common flexor mass. Thompson et al.[31] evaluated eighty-three athletes with medial elbow instability who had undergone medial ulnar collateral ligament reconstruction with a muscle-splitting approach without transposition of the ulnar nerve and showed that 93% had an excellent result. Ahmad et al.[9] described a new medial ulnar collateral ligament reconstruction technique involving interference screw fixation and emphasized the advantage of a limited muscle-splitting approach. Our results demonstrate the importance of the flexor carpi ulnaris and the flexor digitorum superficialis and further emphasize the importance of reducing muscle morbidity during surgical approaches.

Several limitations of our study must be considered. While muscle simulation was performed according to physiological cross-sectional area[18], these magnitude ratios may be greatly exceeded during pitching. Similar to Morrey et al.[14], we used muscle forces that were below physiologic loads, with the goal of demonstrating relative muscle contributions to valgus stability. Our results demonstrate that the biceps, brachialis, and triceps contribute to valgus stability by means of a joint compression effect as previously demonstrated by Morrey et al.[14]. In contrast, the flexor-pronator mass provides stability by means of direct muscle action with vectors that are optimally positioned to resist valgus torque. Our results show that the biceps, brachialis, and triceps simulations were significantly different from the other conditions tested (Figs. 5-A and 5-B), suggesting the independent role of the flexor-pronator mass in valgus stability.

The elbow flexion angles in the present study were limited to 90° and 30° in order to examine the elbow at positions that are representative of the pitching cycle (acceleration and follow-through, respectively). Numerous investigators have used 30° of elbow flexion for manual valgus instability testing as this position helps to unlock the osseous configuration of the relatively constrained ulnohumeral joint[4,32,33]. Sojbjerg et al.[3] revealed that the maximum valgus angles after transection of the medial ulnar collateral ligament were found with the elbow in 60° to 70° of flexion. Other investigators have reported that elbow flexion angles of between 60° and 75° are optimal for revealing valgus instability arthroscopically[33,34]. Callaway et al.[20] showed that clinical testing for complete tears of the anterior bundle should be performed with the elbow in 90° of flexion. In the current study, the number of elbow flexion angles was limited in order to enhance preservation of the elbow specimens during testing. The primary goal was to isolate the effects of muscle-loading on the valgus angle.

In our experiments, the forearm was fixed in neutral rotation; however, pronation and supination have been reported to influence valgus stability[23,34,35]. The possibility exists that forearm rotation affects muscle action. However, in the present study, this factor was held constant in order to isolate the effects of muscle-loading on the valgus angle. Therefore, neutral forearm rotation was tested in all specimens, as has been the case in other studies[3,15,19-21]. The kinematics of the elbow during overhead throwing are complex, with various pitches being associated with a spectrum of forearm rotation; this variable requires additional study.

Notably, the standard deviations for the results are at times larger than the means themselves. This predictably occurs secondary to the anatomic variability between specimens. However, with the commonly used repeated-measures statistical analyses, each specimen can serve as an internal control. Therefore, significance can exist, despite the expected variations in the valgus angle between different specimens.

In summary, based on in vitro biomechanical analyses, the flexor carpi ulnaris and flexor digitorum superficialis can provide significant dynamic stability to the elbow. The flexor carpi ulnaris is the primary dynamic stabilizer, and the flexor digitorum superficialis is a secondary stabilizer. In comparison, the pronator teres provides the least dynamic stability. In addition, since both static ligaments and dynamic muscles appear to share the restraining forces to valgus torques, muscle injury and dysfunction may explain the onset of symptoms in throwers with underlying elbow laxity or insufficiency. When considering injury prevention, surgical techniques, and rehabilitation for athletes who perform overhead throwing motions, the physician should give particular attention to optimizing the function of the flexor carpi ulnaris and flexor digitorum superficialis muscles. ■

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