

MEDIAL COLLATERAL LIGAMENT STRAIN WITH PARTIAL POSTEROMEDIAL OLECRANON RESECTION

A BIOMECHANICAL STUDY

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Background: Partial resection of the posteromedial aspect of the olecranon in the treatment of valgus extension impingement osteophytosis is a well-described technique. It has been hypothesized that removal of the normal olecranon process, beyond the osteophytic margin, increases the strain in the anterior bundle of the medial collateral ligament.

Methods: We used an electromagnetic tracking device to investigate the strain in the anterior bundle of the medial collateral ligament as a function of increasing applied torque and posteromedial resections of the olecranon in seven cadaveric elbows. Applied torques under valgus stress consisted of hand weight, hand weight plus 1.75 Nm, and hand weight plus 3.5 Nm. Resections were conducted in sequential 3-mm increments, from 0 to 9 mm. We measured changes in the length of the anterior and posterior bands of the anterior bundle of the medial collateral ligament with strain gauges. The strains of the two bands were averaged, and the average was reported.

Results: The strain in the anterior bundle of the medial collateral ligament was found to increase with increasing flexion angle, valgus torque, and olecranon resection beyond 3 mm. In two elbows, the anterior bundle of the medial collateral ligament ruptured during testing following the 9-mm resection. There was a significant difference between the strain following the 6-mm resection and that following the 3-mm resection at 110° of flexion with 3.5 Nm of added torque ($p = 0.004$).

Conclusions: In this in vitro cadaver study, an increase in flexion angle, an increase in valgus torque, and resection of ≥ 6 mm led to an increase in strain in the anterior bundle of the medial collateral ligament. The non-uniform change in strain related to 3 mm of resection suggests that resections of the posteromedial aspect of the olecranon of >3 mm may jeopardize the function of the anterior bundle.

Clinical Relevance: Resection of the olecranon beyond the posteromedial osteophytic margin increases the strain in the anterior bundle of the medial collateral ligament, with the potential for a consequent ligament rupture. We advise resection of the osteophytes only.

Throwing athletes are prone to chronic elbow injuries as a result of the repetitive nature of the high loads experienced by the elbow. A specific example is impingement of the posteromedial aspect of the olecranon process on the lateral aspect of the medial humeral column posteriorly^{1,2}. A consequence of this valgus extension overload syndrome is the development of symptomatic osteophytes on the posteromedial aspect of the olecranon¹ in association with a subclinical injury to the medial collateral ligament. Surgical treatment frequently includes resection of a part of the normal olecranon process beyond the osteophytic margin. However, there is no real consensus regarding the safety of this intervention with respect to exposing the medial collateral ligament to excess stress.

We hypothesized that the strain in the anterior bundle of the medial collateral ligament of the elbow increases with increased applied valgus torques and increased amounts of posteromedial resection of the olecranon. The aim of this study was to determine the strain resulting from different amounts of resection of the posteromedial part of the olecranon under different loading conditions.

Materials and Methods

Seven fresh-frozen cadaveric upper extremities from five male and two female donors with an average age of seventy-eight years (range, sixty-two to eighty-nine years) at the time of death were tested. The specimens were stored at -20°C from

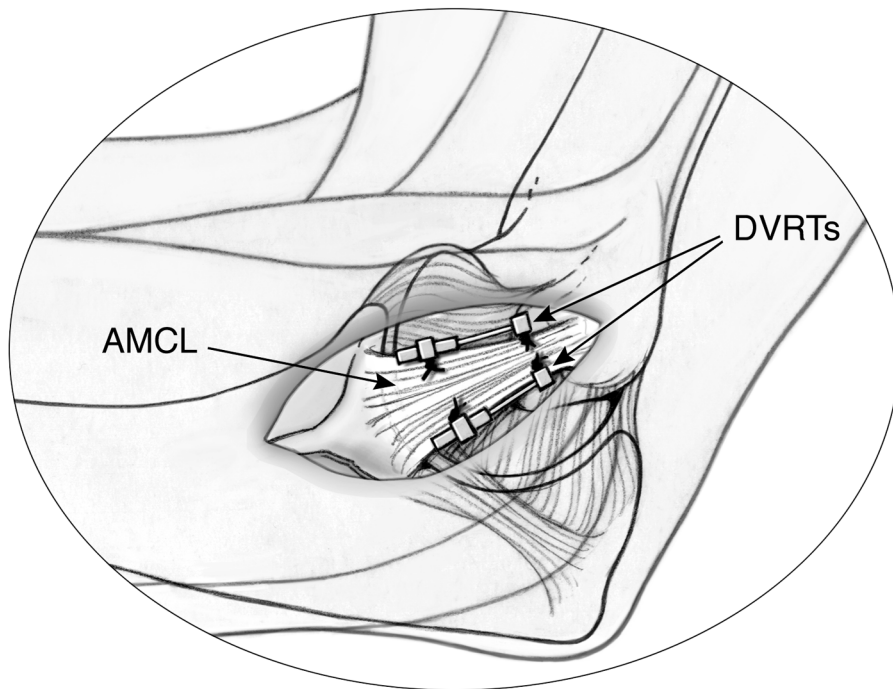


Fig. 1

Schematic representation of the attachment of the differential variable reluctance transducer (DVRTs) to the anterior and posterior bands of the anterior bundle of the medial collateral ligament (AMCL). The posterior bundle of the medial collateral ligament was undisturbed.

the time of retrieval until the time of testing. There were no macroscopic signs of osseous or soft-tissue abnormalities.

Experimental Setup

Each specimen consisted of the arm distal to the midpart of the humeral shaft, the elbow joint, and the forearm including an intact distal radioulnar joint. The humeral shaft was embedded in a Plexiglas tube filled with polymethylmethacrylate. The embedded humerus was inserted into a custom elbow testing table³, which maintained the humerus parallel to the floor. The orientation of the elbow could be adjusted by rotating the arm within the loosened table fixture, thereby allowing subsequent testing to be performed in the neutral, valgus, or varus stress position. The forearm was freely mobile about the elbow joint in pronation and supination.

The biceps brachii, brachialis, and triceps were transected at the midhumeral level, and the latter two were released subperiosteally to the proximal level of the elbow capsule. The biceps brachii, brachialis, and triceps muscles were attached to free hanging weights of 2, 2, and 4 kg respectively⁴. This technique was based on a validated simulated motion and joint compressive loading system that we described previously⁵. In that study, we employed a 1:1:2-kg loading regime; in the current study, we maintained the same loading ratios but doubled the forces. Hence, whereas our previous loading regimen represented 5% of the maximum potential force of the loaded muscle groups, we increased this to 10% of the maximum potential force in the present study since we expected baseball pitchers to generate much larger forces. Because of the experimental limits of the sutures placed in the tendons, this was the maximum load that could be applied.

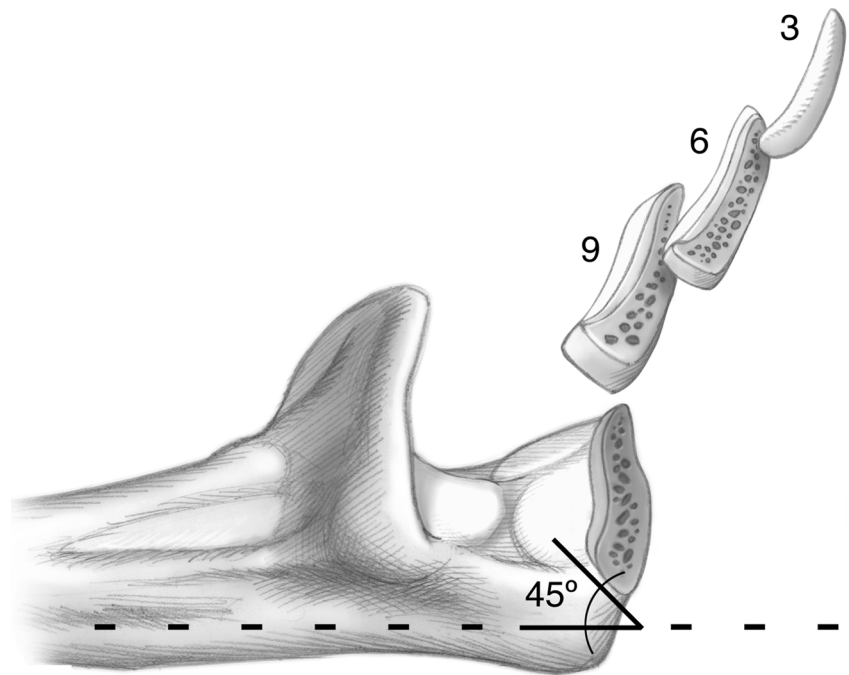
In the valgus or varus stress positions, weights were at-

tached to the radial styloid process, simulating the weight of the resected hand. Elbow kinematics were recorded by a three-dimensional electromagnetic tracking system (3Space Fastrak; Polhemus, Colchester, Vermont).

The anterior bundle of the medial collateral ligament complex was exposed with use of a flexor-pronator mass-splitting approach. The anterior and posterior margins were defined from their humeral to their ulnar attachments, without disturbing the posterior bundle. A differential variable reluctance transducer (MicroStrain, Williston, Vermont) was attached to the surfaces of the anterior and posterior margins of the anterior bundle (Fig. 1). The transducer was 11 mm in length at the insertion, had a barrel diameter of 1.5 mm, and had a height, including the barrel height and the anchoring attachments, of 3 mm. The transducer was attached by sewing it directly to the anterior bundle of the medial collateral ligament with 5/0 Vicryl suture in a box suture arrangement consisting of two individual sutures per anchorage point, a method similar to that employed by Pribyl et al.⁶. This method was found to be reliable with respect to resisting slippage relative to the ligament. In addition, the offset between the ligament surface and the moving part of the differential variable reluctance transducer was minimized, thereby reducing the tendency for cantilever bending. To prevent impingement on the surrounding muscle, <5% of the muscle was resected, without compromising the whole structure of the flexor-pronator mass.

Prior to each test, a calibration was performed for each differential variable reluctance transducer, in which a voltage output was correlated to a displacement (in millimeters). The linear range of the transducer was thus defined, over a range of displacements, and it was positioned onto the ligament such that the minimum dimension of the ligament was situ-

Fig. 2
Diagrammatic illustration of the three levels
of posteromedial resection of the olecranon:
3, 6, and 9 mm.



ated at the proximal part of the linear range of the transducer. The converted displacements were then used to calculate strain with the formula: $([\text{length at flexion angle studied} - \text{length at } 50^\circ \text{ of flexion in an intact elbow loaded with hand weight only}] / \text{length at } 50^\circ \text{ of flexion in an intact elbow loaded with hand weight only}) \times 100$.

Additional valgus and varus loads were applied to the forearm during testing. All specimens had the weight of the hand attached as well as additional loads as determined by the desired increase in torque; the latter varied depending on the cadaver anatomy. The additional loads were based on 5% and 10% of the ultimate resistive varus torque (34.6 Nm) borne by the medial collateral ligament⁷ and ranged from 580 to 1380 g. The loads were added to the forearm in the form of bags of saline solution attached to the radial styloid process.

Olecranon resections were performed in sequential 3-mm steps with use of a 0.4-mm-thick oscillating saw (Hall Oscillator; Zimmer, Warsaw, Indiana). The saw blade was oriented at 45° to the subcutaneous border of the ulna, remaining parallel to the posteromedial border of the olecranon⁸. The conditions of olecranon resection that were tested were an intact elbow and 3, 6, and 9 mm of resection (Fig. 2).

Testing Sequence

The same sequence of testing was maintained for the different test parameters. Testing began in the neutral position, with the humerus and the transepicondylar line parallel to the floor. Passive elbow extension was performed from a position of full flexion with two nylon cords attached to the base of the ulnar styloid process, taut in the plane of the flexion arc. Each individual condition was tested in duplicate, and the results of the two tests were averaged. The elbow was then positioned in the testing table in a varus stress position, with the transepicondy-

lar line perpendicular to the floor, the ulna inferior, and the radius superior. The testing sequence was repeated with incremental 5% and 10% varus torques. Finally, the elbow was oriented in the valgus stress position, with the transepicondylar line perpendicular to the floor, the radius inferior, and the ulna superior. The testing sequence was repeated with the incremental 5% and 10% valgus torques. After the testing of the intact elbow was completed, the above testing sequences were repeated sequentially following the three olecranon resections. The ligaments and soft tissues were kept moist throughout the testing with normal saline solution.

After completion of all of the kinematic testing stages, the elbows were disarticulated, and digitization of the articular surfaces, distal part of the humeral shaft, and ulnar styloid process was performed. These data were used to create a coordinate system based on the osseous anatomy with optimized motion.

The collected data consisted of the flexion angles in degrees; valgus-varus displacements in degrees; and measurements, in millimeters, made with the differential variable reluctance transducers. The transducer data were converted from a length measurement to a strain, with the denominator being the minimum value with the intact elbow in a valgus stress position and loaded with hand weight only. Since the literature provides no clear indication regarding the relative functional importance of the anterior and posterior bands of the anterior bundle of the medial collateral ligament⁹, we measured the linear dimensional changes of both bands and reported the average of the summed data, according to the equation: $(\text{anterior band of the anterior bundle of the medial collateral ligament strain} + \text{posterior band of the anterior bundle of the medial collateral ligament strain}) / 2$.

Statistical analysis was performed with use of a two-way repeated-measures analysis of variance, with post-hoc tests

TABLE I Strain at Different Flexion Angles, Loading Conditions, and Levels of Posteromedial Olecranon Resection

Flexion Angle/Loading Condition	Percentage Strain*			
	Intact (N = 7)	3-mm Resection (N = 7)	6-mm Resection (N = 7)	9-mm Resection (N = 5)
50°				
Hand only	0.0 ± 0.0	-3.0 ± 0.4	0.2 ± 0.3	0.3 ± 0.5
Hand + 1.75 Nm	0.5 ± 0.2	0.4 ± 0.4	0.8 ± 0.5	1.8 ± 2.2
Hand + 3.5 Nm	1.1 ± 0.5	1.0 ± 0.6	1.4 ± 0.8	2.5 ± 2.4
70°				
Hand only	1.5 ± 1.0†	1.4 ± 1.1†	1.9 ± 1.1	2.4 ± 1.5†
Hand + 1.75 Nm	2.3 ± 1.1†	2.2 ± 1.3†	2.6 ± 1.3	3.2 ± 1.8†
Hand + 3.5 Nm	2.9 ± 1.2	2.8 ± 1.3	3.2 ± 1.4	3.8 ± 2.3
90°				
Hand only	1.9 ± 1.4†	1.8 ± 1.6†	2.3 ± 1.6†	3.0 ± 2.0†
Hand + 1.75 Nm	2.7 ± 1.8	2.7 ± 1.9	3.1 ± 1.9	3.8 ± 2.5
Hand + 3.5 Nm	3.4 ± 2.0	3.3 ± 2.1	3.7 ± 2.2	4.3 ± 3.2
110°				
Hand only	1.8 ± 2.0†	1.7 ± 2.2†	2.0 ± 1.9†	3.1 ± 2.4†
Hand + 1.75 Nm	2.7 ± 2.3†	2.6 ± 2.5†	3.1 ± 2.4†	4.1 ± 2.6†
Hand + 3.5 Nm	3.4 ± 2.5††	3.4 ± 2.6††	3.9 ± 2.7††	4.8 ± 2.6†

*The percentage strain = the change in strain-gauge length relative to that at 50° of flexion with hand weight only in the intact specimen. The values are given as the mean and standard deviation. †A significant difference ($p < 0.05$) in strain between the 9-mm resection and the lesser resections under the same loading conditions. ††A significant difference ($p < 0.05$) in strain between the 6-mm resection and the lesser resections under the same loading conditions.

(Bonferroni and Scheffé). This allowed characterization of the influence of the condition of the elbow (intact or following resections) and the influence of the flexion angle or simulated loading on the outcome variable (anterior bundle strain). If a significant interaction was determined with the two-way analysis, a one-way repeated-measures analysis of variance or paired t

tests were used to compare groups that showed significant differences. This latter test was used to compare the strain changes between the different resection levels and the intact elbow, at the same flexion angles and loading conditions. Post-hoc corrections were performed with the Bonferroni and Scheffé adjustments. A p value of 0.05 was considered to be significant.

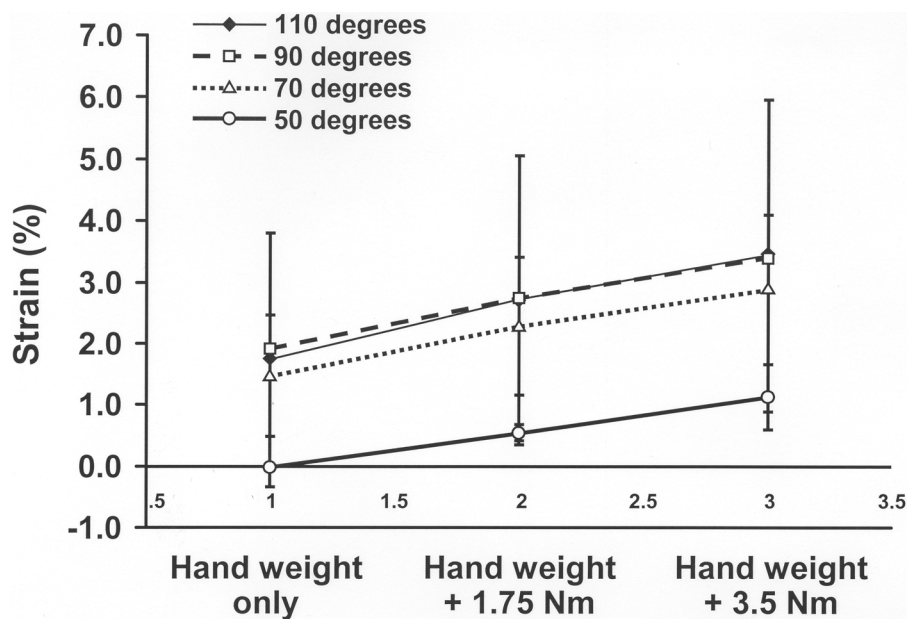
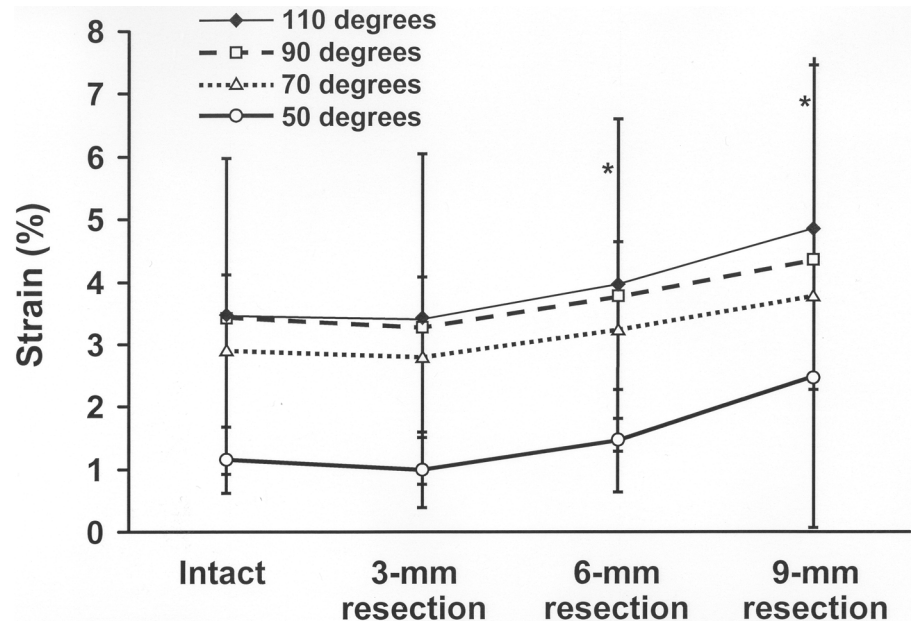


Fig. 3

Strain in the anterior bundle of the medial collateral ligament in an intact elbow, in the valgus stress orientation, as a function of loading condition and at 50°, 70°, 90°, and 110° along the flexion arc. The means and standard deviations are shown.

Fig. 4

Strain in the anterior bundle of the medial collateral ligament in the intact elbow and after 3, 6, and 9 mm of resection at 50°, 70°, 90°, and 110° along the flexion arc. The elbows were in a valgus stress orientation, with the hand weight plus an additional 3.75 Nm. The means and standard deviations are shown.



Results

In the intact state, with the elbow in the valgus stress position, there was a linear increase in strain with increasing applied torque (Fig. 3, Table I). This relationship appeared consistent between specimens with flexion up to 70° but became less predictable with flexion of about 90°.

Three millimeters of resection did not consistently alter the strain in the anterior bundle of the medial collateral ligament when compared with the value in the intact state; the strain increased in two cadavers and decreased in five. This amount of resection yielded strain values similar to those in the intact state at all angles of flexion and under the different loading conditions (Fig. 4). Sequentially larger strains were demonstrated after the 6 and 9-mm resections. The 6-mm resection resulted in an increase in strain of 27% at 50° of flexion (the difference between the intact specimen and that following the 6-mm resection with a 3.5-Nm torque) and 15% at 110° of flexion (the difference between the intact specimen and that following the 6-mm resection with a 3.5-Nm torque). The 9-mm resection resulted in an increase in strain of 127% at 50° of flexion (the difference between the intact specimen and that following the 9-mm resection with a 3.5-Nm torque) and 41% at 110° of flexion (the difference between the intact specimen and that following the 9-mm resection with a 3.5-Nm torque). The mean maximum strain (and standard deviation) recorded for the medial collateral ligament was 4.8 ± 2.6 , after the 9-mm resection, with a 3.5-Nm torque, and in 110° of flexion.

At 50° of flexion, none of the resections caused significant differences in the strain in the anterior bundle of the medial collateral ligament (Table I). At 70° of flexion, a 9-mm resection significantly increased the strain in the anterior bundle both with hand weight ($p = 0.01$) and with hand weight plus 1.75 Nm of torque ($p = 0.04$) when compared with the values for the intact state and after the 3-mm resection. At 90° of flexion, a 9-mm resection significantly increased the strain

in the anterior bundle with hand weight when compared with the values in the intact state and after the 3 and 6-mm resections ($p = 0.02$). At 110° of flexion, a 9-mm resection significantly increased the strain in the anterior bundle with hand weight ($p = 0.04$), hand weight plus 1.75 Nm ($p = 0.02$), and hand weight plus 3.5 Nm ($p = 0.004$) when compared with the values for the intact state and after the 3 and 6-mm resections. At 110° of flexion, a 6-mm resection significantly increased the strain in the anterior bundle with hand weight plus 3.5 Nm ($p = 0.004$) when compared with the values in the intact state and after the 3-mm resection. The range of strains that was recorded within this experiment was 0% (at 50° of flexion in valgus orientation without resection or additional weight) to +8.5% (at 110° of flexion in valgus orientation after the 9-mm resection and with 3.5 Nm of added torque).

Two specimens, one left and one right, from donors who had been eighty-seven and eighty-nine years old at the time of death sustained a complete rupture of the anterior bundle of the medial collateral ligament after 9 mm of resection when tested with 3.5 Nm of torque in the valgus stress position. Each had avulsed from its origin on the medial epicondyle. Prior to these ruptures, the strain gauge data had demonstrated failure by plastic deformation in both specimens during the test involving the 9-mm resection and hand weight only. The results prior to the 9-mm resections of these specimens were included for subsequent analysis, with exclusion of the data under the final (9-mm) resection condition. Hence the sample size was reduced by two in the analysis of the effect of the 9-mm resection because of the macroscopic failures.

Discussion

The recognition of the importance of the medial collateral ligament of the elbow as the primary valgus stabilizer⁵ has led to a number of studies to analyze its biomechanical behavior and properties. Regan et al.¹⁰ studied the mechanical properties

of the isolated anterior bundle of the medial collateral ligament, which demonstrated 30% strain prior to failure. That study was conducted with a bone-ligament-bone preparation of the anterior bundle of the medial collateral ligament distracted between the jaws of a modified strain extensometer. More recent studies have added to the knowledge of the normal biomechanical properties of the intact anterior bundle of the medial collateral ligament. Pribyl et al.⁶, using a strain gauge on upper limbs with most of the soft-tissues present but without muscle loading, reported a range of strains from 7.5% to 30%. Andrews et al.¹¹ used a strain gauge on osteoligamentous preparations and reported a range of strains to failure from 3% to 21%, with an average of 12%. Our results appear to agree with the lower ends of the ranges of those three studies. We measured a range of strains, for all test conditions, from -1% (at 50° of flexion) to +8.5% (at 110° of flexion) after 9 mm of resection and with an additional 3.5 Nm of applied torque.

Methodological differences between our study and similar studies may explain some of the discrepancies between the reports. It is difficult to distinguish the relevance of an isolated ligament from that of other stability-conferring structures, notably the flexor-pronator mass, and that of muscular joint loading¹⁰. The use of osteoligamentous preparations, as opposed to whole cadaveric upper limbs with all soft-tissues present, may well account for the differences between the observations made by Andrews et al.¹¹ and those in our study. The anatomical blend of the flexor-pronator muscle mass and the underlying anterior bundle of the medial collateral ligament that was demonstrated in all seven specimens in our study suggests a close functional relationship between the two structures^{2,12,13}. This finding suggests that removing the flexor-pronator mass and the other soft-tissues would further disturb the functional integrity of this structural unit. Thus, outcomes of tests of osteoligamentous preparations may well overestimate the ligamentous strains relevant to the clinical situation, which is more accurately represented when the anterior bundle of the medial collateral ligament is isolated from the flexor-pronator mass, as it was in our study.

In addition, the lack of preload with hand and soft-tissue weight allows the starting ligament length to be in the toe region, prior to the linear elastic region of the stress-strain curve. With the preload provided by the weight of the intact soft tissues and the hand weight, we assumed that our results began within the elastic linear range of the ligaments; however, we did not formally conduct tests to confirm this assumption. The results of Pribyl et al. may have also overestimated the strains, since the authors reflected the whole flexor-pronator mass to reveal the anterior and posterior bundles of the medial collateral ligament⁶.

Surgical resection of the posteromedial aspect of the olecranon process in addition to osteophytes that developed as a sequela of the valgus extension overload syndrome¹ is a common practice. However, the anterior bundle of the medial collateral ligament, which is recognized to be the primary structure of valgus restraint¹⁴, has anecdotally been observed to rupture following such resections¹³. Does the resection of

posteromedial olecranon bone beyond the osteophytic margin place the anterior bundle of the medial collateral ligament under greater risk of rupture as a function of the stress placed on it? We were unable to directly answer that question by measuring the stress experienced by the anterior bundle of the medial collateral ligament as a function of increasing olecranon resections. However, we were able to demonstrate consistently increasing strains when we compared 9-mm resections to lesser resections. After resection of 3 mm, the strain was not significantly increased on average but it was increased significantly in two of the seven specimens, which were not the two specimens that subsequently ruptured after 9 mm of resection. Hence, we were unable to predict which specimens would tolerate a 3-mm resection without a resultant increase in anterior bundle strain.

A valgus torque of 64 Nm has been demonstrated in the upper extremity of high-level throwing athletes⁷, with 54% of the torque resisted by the medial collateral ligament at 90° of flexion¹⁴. In our study, in which we used a maximum valgus torque of 3.5 Nm (considerably less than that measured during high-level throwing actions), the anterior bundle of the medial collateral ligament ruptured after 9 mm of resection in two specimens. The strain-gauge data demonstrated that those ligaments had in fact undergone failure by plastic deformation during the test involving 9 mm of resection and hand weight only as well as the test with an additional 1.75 Nm. These findings corroborate the contention that the static stabilizing function of the anterior bundle of the medial collateral ligament is augmented considerably by other static and dynamic structures during such throwing activities.

We also analyzed data from four points along the flexion arc in 20° increments from 50° to 110°, as that represents an arc encompassing the maximal valgus torque during a pitching action⁷. No formal analysis of the varus data was included in this study, since varus torque does not directly influence the strain behavior of the anterior bundle of the medial collateral ligament, but the varus data are presented in a kinematic analysis of this investigation⁸.

This study had a number of limitations. First, although the main area of interest for such data is the management of young throwing athletes, the cadaveric elbows that we tested were from elderly people. Thus, age-related changes to the ligaments should be borne in mind when extrapolating these data to a younger athletic population. The effect of aging on the properties of the ligaments has been reported to be an increase in stress to failure and a decrease in strain to failure¹⁵.

A second limitation of the study is related to the previously documented^{6,11} technique for use of the differential variable reluctance transducers to measure the change in the lengths of the elbow ligaments. The differential variable reluctance transducer is an instrument that functions optimally when the length change is in a single plane, notably pure axial shortening or lengthening within the linear range of the device. However, with valgus angular displacements about the elbow, the medial collateral ligament lengthens under multi-axial, not uniaxial, loading conditions. Valgus displacements

of the elbow are the results of axial loading, bending, and torsion of the anterior bundle of the medial collateral ligament. The latter two modes of ligamentous stretching cannot be determined with use of the differential variable reluctance transducer technique. Therefore, the absolute quantitative data presented in this study may underestimate the amount of strain experienced by this ligament, as is true of other studies utilizing this technique.

Our study was also limited by the fact that, as a result of the nature of prolonged and repetitive testing, the integrity and function of the soft-tissue structures may have been compromised. Although changes were not observed macroscopically, microscopic changes cannot be ruled out. Finally, although the importance of the flexor-pronator mass for dynamic stabilization of valgus displacements has been reported², with some confounding contrary data¹⁶, we did not incorporate the flexor-pronator mass into the testing setup. The inherent association of the flexor-pronator mass with the anterior bundle of the medial collateral ligament had to be dissected to be able to place the differential variable reluctance transducers. Additionally, <5% of the muscle had to be resected to prevent undisturbed excursions of the transducers. Both of these necessary procedures altered the function of the anterior bundle of the medial collateral ligament. It is our belief that the anterior bundle of the medial collateral ligament and the flexor-pronator mass act as an integral unit to resist valgus stresses, with both passive and dynamic modes. However, with our strain-gauge methodology, our experimental modifications were unavoidable.

We attempted to define the strain characteristics of the anterior bundle of the medial collateral ligament in relation to both increasing valgus stresses on the elbow and increasing posteromedial resections of the olecranon. Although there were attempts to answer the same questions in a previous study, that study involved osteoligamentous preparations¹¹, which we believe confounded the data. In the current study, we tested intact fresh-frozen upper limbs with minimal disturbance of the surrounding soft-tissue envelope, although we recognize that there

was some degree of disturbance due to our methodology. Our findings support the belief that resection of the posteromedial bone of the olecranon beyond the osteophytic margin potentially places the anterior bundle of the medial collateral ligament in jeopardy of rupture. Although our average strain results after the 3-mm resection suggest that that resection is safe, the inability to predict which individuals would experience increased strains after that amount of resection suggests that even a 3-mm resection may not be safe. Our recommendation, therefore, is to resect the osteophytes only. ■

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The authors did not receive grants or outside funding in support of their research or preparation of this manuscript. They did not receive payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, educational institution, or other charitable or nonprofit organization with which the authors are affiliated or associated.

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