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Evaluation of anterior oblique ligament tension at the elbow joint angle—a cadaver study

Yusuke Matsuura, MD, PhD[a,*], Takashi Takamura, MMSc[b], Shiro Sugiura, PhD[c], Yoshiyuki Matsuyama, MD, PhD[a], Takane Suzuki, MD, PhD[d], Chisato Mori, MD, PhD[d], Seiji Ohtori, MD, PhD[a]

[a]*Department of Orthopaedic Surgery, Graduate School of Medicine, Chiba University, Chiba, Japan*
[b]*Funabashi Orthopaedic Hospital, Chiba, Japan*
[c]*Nishikawa Orthopaedic Clinic, Chiba, Japan*
[d]*Department of Bioenvironmental Medicine, Chiba University, Chiba, Japan*

Background: The ulnar collateral ligament complex, particularly the anterior oblique ligament (AOL), is mainly a static stabilizer controlling valgus. Various studies have been conducted on the kinematics of elbow joints after ligament cutting; however, no biomechanical studies have measured the tension applied to the ligament. Finite element modeling (FEM) is a very useful tool for biomechanical evaluation of the elbow. However, an accurate FEM of elbow joints cannot be developed without information on the potential tension of ligaments applied during the flexion and extension of elbow joints. We believe that FEM of the elbow joint could be obtained by measuring the material properties and potential tension of the ligament applied during the flexion and extension of the elbow joint. This study aimed to measure the potential tension and material properties of the ligament during the flexion and extension of the elbow, by identifying the relation between ligament length and tension using mechanical testing.
Methods: We included 10 elbows harvested from 7 fresh-frozen cadavers. The average age of the cadavers was 83.7 ± 5.65 years, and the samples included 8 elbows from 6 male cadavers and 2 elbows from 1 female cadaver. We measured the ligament length at each elbow angle by changing the elbow joint from 0° to 120° in 15° intervals. Thereafter, we extracted the AOL and divided into an anterior band (AB) and a posterior band (PB) and performed a mechanical test to calculate ligament stress.
Results: The ligament length of the AB gradually decreased as the flexion angle increased. Conversely, the ligament length of the PB gradually increased as the flexion angle increased. AB and PB lengths were approximately the same between 60° and 75°. The average ligament tension and stress of the AB gradually increased with elbow extension. In contrast, the average ligament tension and stress of the PB gradually increased with elbow flexion. The tension and stress of the AB and PB were balanced around the elbow joint at 60°.
Conclusion: The AB was tenser on elbow extension, and the PB was tenser following elbow flexion. Also, the angle at which the AOL stress was equalized was 60°, suggesting that ∼60° is the angle at which the AOL is unlikely to be damaged.
Level of Evidence: Basic Science Study; Biomechanics

Keywords: Ulnar collateral ligament complex; anterior oblique ligament; biomechanical; tension; stress; material property

To effectively treat elbow instability, it is essential to understand the various structures involved in stability. Elbow joint instability can result from dislocation due to trauma or repeated valgus from playing sports. In addition to osseous constraints, the elbow joint has several important soft tissue

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*Reprint requests: Yusuke Matsuura, MD, PhD, Department of Orthopaedic Surgery, Graduate School of Medicine, Chiba University, 1-8-1 Inohana, Chuo-ku, Chiba, 260-8670, Japan.

E-mail address: y-m-1211@khaki.plala.or.jp (Y. Matsuura).

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stabilizers. Static soft tissue stabilizers consist of the anterior and posterior joint capsules and both the medial and lateral collateral ligaments. Muscles beyond the elbow joint, such as the flexor and extensor muscles of the forearm, bicep muscles, and tricep muscles, function as dynamic stabilizers. The ulnar collateral ligament has a complex function, mainly as a static stabilizer that controls valgus oscillation, and is composed of an anterior oblique ligament (AOL), a posterior oblique ligament, and a transverse ligament. Although the ulnar collateral ligament as a whole suppresses valgus and internal rotational loads, the AOL is generally considered to be the primary suppressor and stabilizer.[2,5,6,8] The AOL is made of thick parallel fibers with an average width of 4-5 mm.[1] It is functionally composed of an anterior band (AB) and a posterior band (PB). The AB functions as the primary restraint of the elbow joint from 0° to 60°, and the PB is the primary restraint from 60° to 120° of flexion. These AB and PB tensions provide an interaction that resists valgus stress throughout the entire range of flexion and extension movements.[2,7,8]

Various studies have been conducted on the kinematics of the elbow joint after ligament cutting,[3,4,9] but there are no mechanical reports that measure ligament tension. Studies using a fresh-frozen cadaver can measure the distance of the ligament, but they cannot directly measure the tension and stress distribution in the ligament. Finite element modeling (FEM) is a very useful tool for biomechanical evaluation. FEM can be used to predict the tension and stress distribution on the ligament. However, many valgus stress tests cannot be evaluated using FEM unless the potential tension of the ligament and the elastic modulus values of the ligament accompanying elbow flexion and extension are obtained.

We proposed that the FEM of the elbow joint could be obtained by measuring the material properties and potential tension of the ligament applied during the flexion and extension of the elbow joint. The purpose of this study was to measure the potential tension and material properties of the ligament during flexion and extension of the elbow by identifying the relation between ligament length and tension using mechanical testing.

Materials and methods

Specimens

This was a biomechanical study using fresh-frozen cadavers. We included 10 elbows obtained from 7 fresh-frozen cadavers. The average age of the cadavers was 83.7 ± 5.65 years, and the samples included 8 elbows from 6 male cadavers and 2 elbows from 1 female cadaver. The exclusion criteria included upper limb paralysis cases, elbow contracture cases, elbow osteoarthritis cases, and a history of trauma.

Preparation

We amputated the specimens at the middle of the humerus. We dissected the medial collateral ligament using an elbow joint medial approach. To isolate the AOL, the posterior oblique ligament, the anterior and posterior joint capsules, and the forearm flexors were resected. The forearm and the wrist were fixed at a neutral position. Through the steel wire on the joint side of the AOL, the proximal position of the distal attachment part of the AOL and the most distal portion of the proximal attachment part were identified. We inserted a Kirschner wire (K-wire) with a diameter of 1.0 mm into the anterior of the proximal part, the posterior of the proximal part, the anterior of the distal part, and the posterior of the distal part, and these were used as measurement markers. The distance between the anterior (A) of the proximal part and anterior (B) of the distal part measurement markers in the anterior AOL and the distance between the posterior (C) of the proximal part and posterior (D) of the distal part measurement markers in the posterior AOL were defined as the AB length and PB length, respectively (Fig. 1). AB and PB lengths were measured with a digital venire caliper (Absolute Digimatic Caliper; Mitutoyo Corporation, Kawasaki, Japan), which has a sensitivity of ±0.02 mm, when the elbow joint angles were at 15° intervals from 0° to 120° (Fig. 2).

Mechanical test

We performed the mechanical tests using a universal testing machine (Autograph AG-20kN X Plus; Shimadzu, Kyoto, Japan) (Fig. 3). First, we removed the AOL containing the measurement markers and divided it into the AB and PB at the AOL midline (Fig. 3, *a*). Using 6-0 Ethilon (Ethicon, Somerville, NJ, USA), we measured the circumference of each band with an Absolute Digimatic Caliper and calculated the cross-sectional area of each band. The proximal and distal ends of each band were grasped together with the bone using a jig (Fig. 3, *b*). The jig was connected to a mechanical testing machine, and the length of each band was measured using an Absolute Digimatic Caliper (Fig. 3, *c*). The traction test was performed at a speed of 5 mm/min, without applying a preload, until failure occurred in the bone grip. A displacement-force curve was obtained (Fig. 4, *a*).

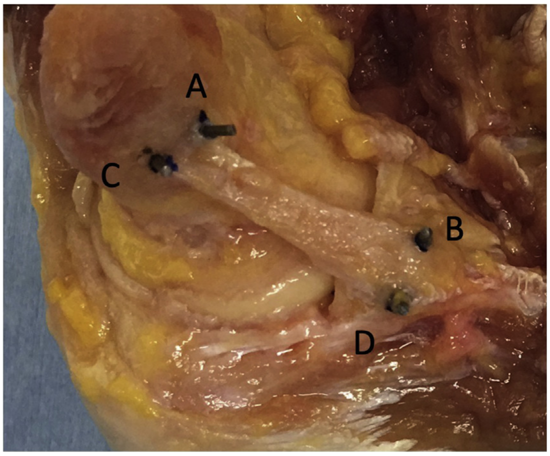


Figure 1 Anterior oblique ligament (AOL) and inserted K-wire as markers for measuring ligament length: **A**, anterior part of AOL proximal insertion; **B**, anterior part of AOL distal insertion; **C**, posterior part of AOL proximal insertion; **D**, posterior part of AOL distal insertion.

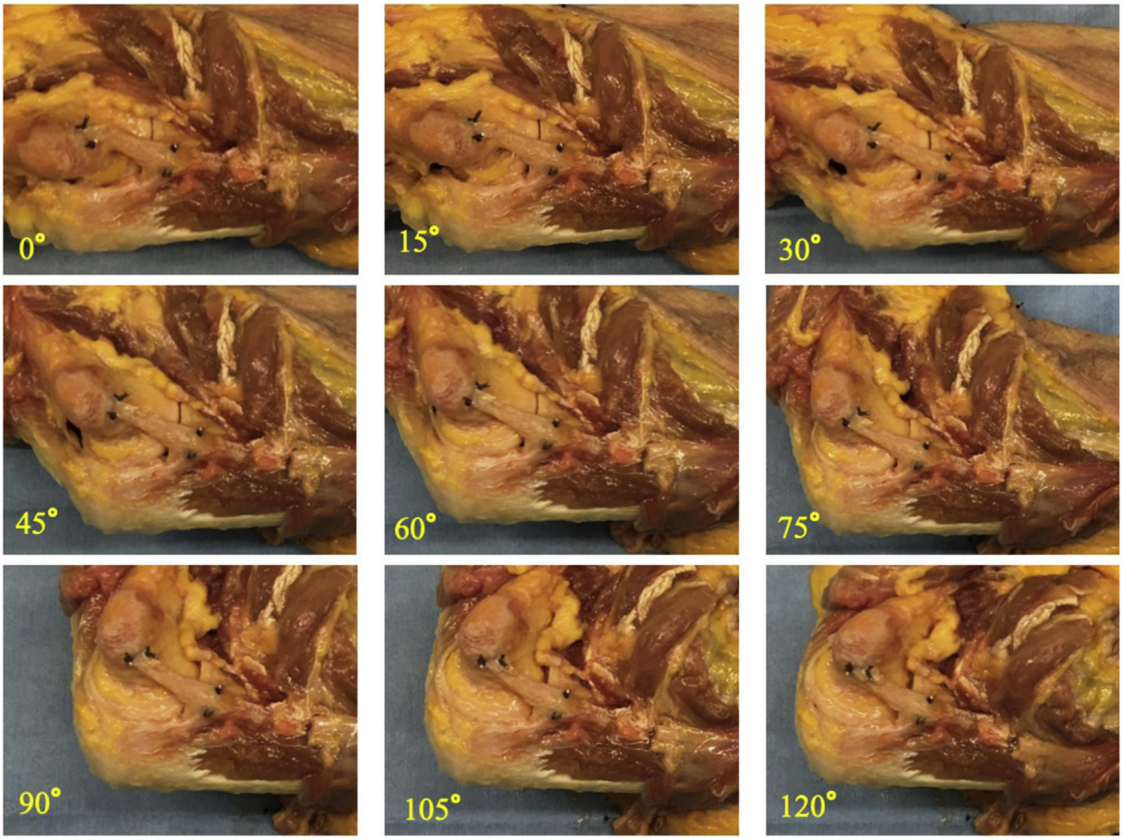
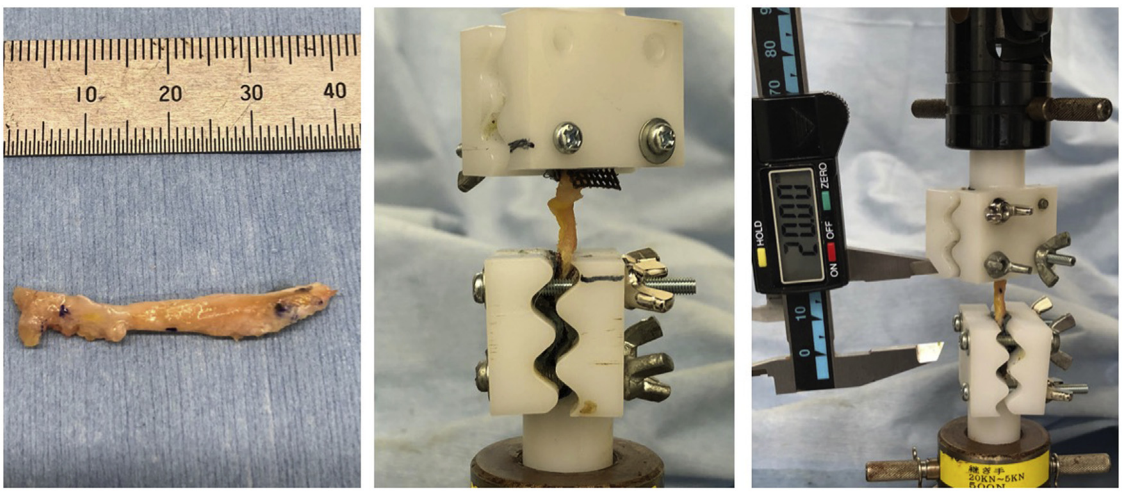


Figure 2 Anterior oblique ligament in each elbow angle.

Analysis

The displacement-force curve was converted into a band length–force curve using each band length that was determined when they were connected to a mechanical testing machine. Furthermore, a plot generated after failure extended the linear part of the curve and complemented it (Fig. 4, *b*). From the ligament length–force curve obtained by a mechanical test, each band length for each elbow joint angle was converted into ligament tension. The ligament stress for each joint angle was calculated by



a b c

Figure 3 Mechanical test of AOL: (**a**) anterior band; (**b**) the sample was fixed with a custom-made jig; (**c**) measurement of the length of each band when the band is connected to the jig.

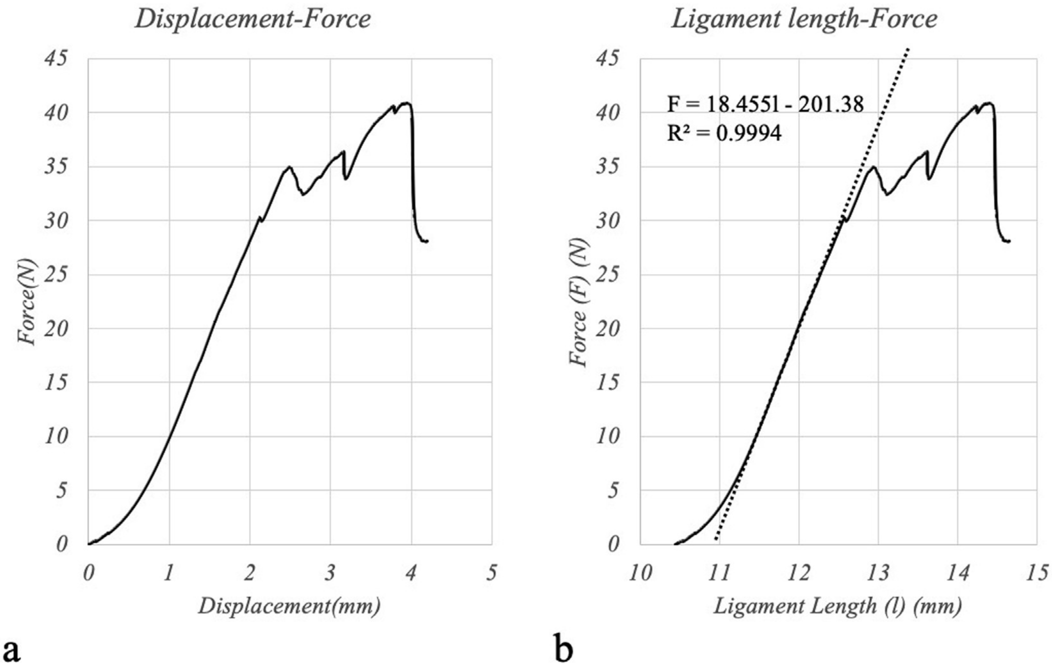


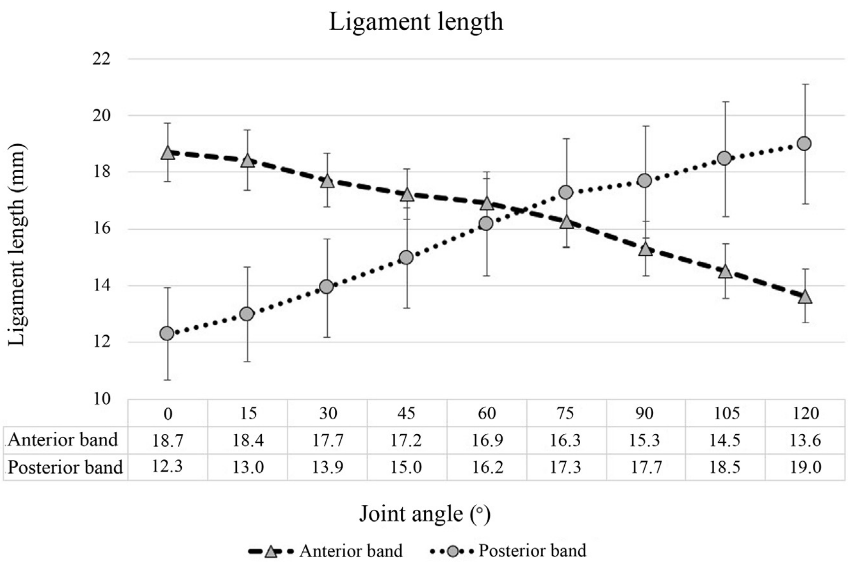
Figure 4 A plot of mechanical test: (**a**) the displacement-force curve; (**b**) complement of the plot after failure extended as the linear part.

dividing the tension of each band by the cross-sectional area. In addition, the band length–band tension and band length–band stress relations were calculated from the average band length, average band tension, and average band stress at each joint angle.

Results

The average length (standard error [SE]) of the AB was 18.7 mm (SE, 1.0) at 0°, and as the flexion angle increased, the length gradually decreased to 13.6 mm (SE, 0.9) at 120°. In contrast, the average length of the PB was 12.3 mm (SE, 1.6) at 0°, and as the flexion angle increased, the length gradually increased to 19.0 mm (SE, 2.1) at 120° (Fig. 5). The lengths of the AB and PB were similar between 60° and 75°.

The average tension force of the AB was 40.5 N (SE, 8.59) at 0°, and as the flexion angle increased, the force gradually decreased to 0.37 N (SE, 0.18) at 120°. Conversely, the average tensile force of the PB was 0.36 N



	0	15	30	45	60	75	90	105	120
Anterior band	18.7	18.4	17.7	17.2	16.9	16.3	15.3	14.5	13.6
Posterior band	12.3	13.0	13.9	15.0	16.2	17.3	17.7	18.5	19.0

Figure 5 Relation between elbow joint angle and ligament length.

(SE, 0.24) at 0°, and as the flexion angle increased, the tension force gradually increased to 77.6 N (SE, 17.6) at 120° (Fig. 6). The tension force of each band was balanced around the elbow joint at 60°.

The average tension stress of the AB was 3.4 MPa (SE, 0.78) at 0°, and as the flexion angle increased, the tension stress gradually decreased to 0.02 MPa (SE, 0.01) at 120°. Conversely, the average tension stress of the PB was 0.05 MPa (SE, 0.04) at 0°, and as the flexion angle increased, the tension stress gradually increased to 6.18 MPa (SE, 1.23) at 120° (Fig. 7). The tensile stress of each band was balanced at 60° around the elbow joint.

The relational equations of ligament length (l) and ligament tension (F) of the AB (equation 1) and PB (equation 2) are shown below (Fig. 8).

$$F = 0.27l^2 - 1.32l - 31.4 \qquad \text{Equation 1}$$

$$F = 1.26l^2 - 28.6l + 158.9 \qquad \text{Equation 2}$$

The relational equations of ligament length (l) and ligament stress (σ) of the AB (equation 3) and PB (equation 4) are shown below (Fig. 9).

$$\sigma = 0.033l^2 - 0.42l - 0.45 \qquad \text{Equation 3}$$

$$\sigma = 0.15l^2 - 3.77l + 23.8 \qquad \text{Equation 4}$$

Discussion

In this study, we investigated the relation between joint angle and the potential tension applied to the ligament, the relation between the joint angle and the ligament fiber length of the elbow joint, and the relation between the ligament length and the ligament tension, using fresh-frozen cadavers. The AB of the AOL had the highest tension when the elbow was extended, and the PB of AOL had the highest tension following elbow flexion.

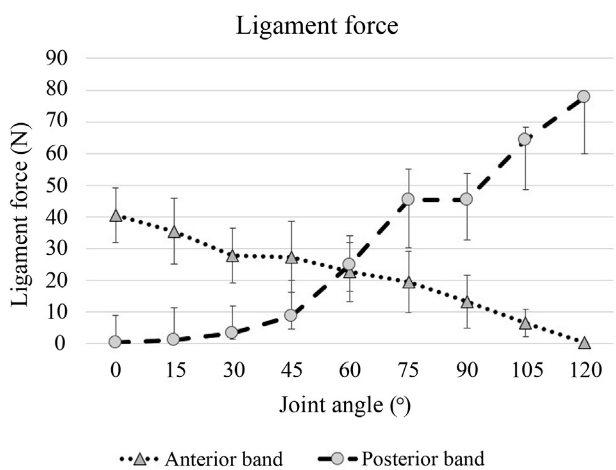


Figure 6 Relation between elbow joint angle and ligament force.

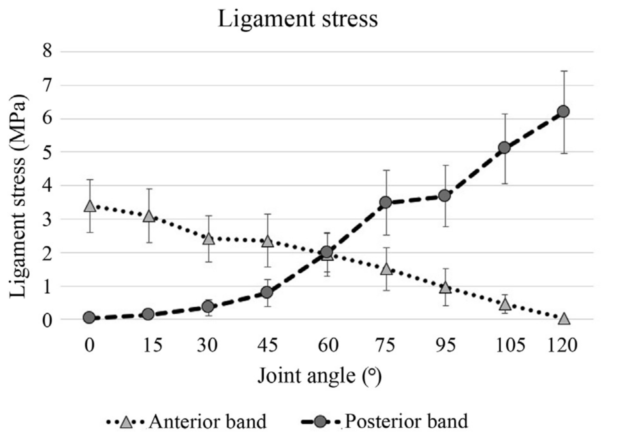


Figure 7 Relation between elbow joint angle and ligament stress.

Wavreille et al[10] measured fiber lengths of the ABs and PBs and reported similar distances that were between 30° and 60°. In this study, the distance between AB and PB was equal when the elbow angle was approximately 60°-75°, which was consistent with previous findings. However, the ligament length and tension are not synonymous. In other words, it was expected that tension would not be generated with a ligament length below a certain value. In fact, from this study, the AB almost lost tension as the elbow flexion angle increased, and the PB lost tension as the elbow flexion angle decreased. In contrast, the ligament tension became uniform at approximately 60° of the elbow joint in this study. From this result, at the elbow joint angle where the ligament tension is equally applied to AB and PB, valgus stress is applied evenly across the entire AOL. Therefore, ligament damage is at least likely to occur with the elbow joint at approximately 60°. On the other hand, we presume that strong tension is generated in the region where the length of the ligament is the longest, and where ligament damage is likely to occur. Tension in the AB increased as the elbow was extended, and tension in the PB increased as the elbow was flexed. In other words, it was

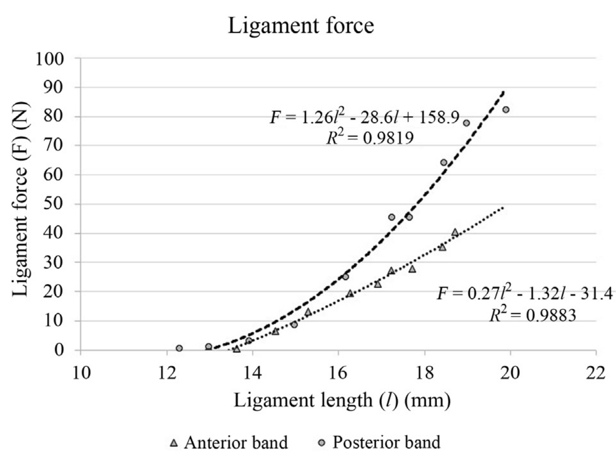


Figure 8 Relation between ligament force and ligament length.

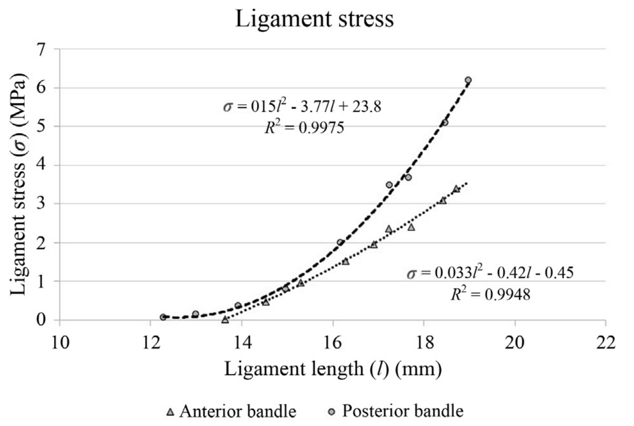


Figure 9 Relation between ligament stress and ligament length.

suggested that when valgus stress occurs during the extension of the elbow joint, damage occurs in the anterior part of the AOL, and when valgus stress occurs during flexion of the elbow joint, damage occurs in the posterior part of AOL.

In this study, the stress associated with each fiber length of the ABs and PBs was calculated. Based on these data and the ligament length for each joint angle, the material properties for each joint angle are determined, and a finite element model can be created. The finite element model generated using these basic data can be applied to the elucidation of various disease states and can be used in surgical planning.

There are various limitations to this study. First, the number of specimens was small. However, all 6 specimens showed a certain tendency, which is considered a valid result. Second, the samples were from elderly people and skewed toward men; therefore, it may be inappropriate to fit the data directly into a younger and/or female model. Third, this study did not include static stability elements other than the AOL, such as the anterior and posterior joint capsules and posterior oblique ligament, or dynamic stability elements, such as muscles and the intermuscular septum. Forearm flexors interact with 2-stage stabilizers of elbow valgus; however, its effect on valgus force stabilization cannot be neglected. Nevertheless, the primary objective of this study was to understand the pathology of AOL rupture, and therefore, it does not reflect all clinical aspects.

Conclusion

The AB was tense as the elbow was extended, and the PB was tense following elbow flexion. In addition, the angle at which the AOL stress was equalized was 60°, suggesting that 60° is the angle at which the AOL is unlikely to be damaged. The study results make it possible to analyze the medial component of the elbow joint using FEM, which could be applied to elucidate the mechanism of throwing elbow joint disorder.

Disclaimer

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