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Original Research

Measurement of the Material Properties of the Triangular Fibrocartilage Complex

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Purpose: The triangular fibrocartilage complex (TFCC) serves to stabilize the distal radioulnar joint, but the stress distribution within the TFCC under dynamic loading is unknown. Finite element analysis (FEM) can be used to investigate the stress distribution, but its accuracy depends on knowing the material properties of the TFCC. The aim of this study was to evaluate the material properties of the TFCC using cadaveric specimens.
Methods: We obtained 12 upper limbs (6 right and 6 left) from 6 fresh-frozen cadavers (3 women and 3 men). Average age at death was 78.3 years (range, 69–87 years). Using a dorsal approach, we dissected each component of the TFCC. We performed tensile and compressive testing with a mechanical testing machine. Young's modulus was calculated from the slope of the linear part of the stress–strain curve.
Results: The Young's modulus was 7.0 ± 2.4 MPa in the volar component, 8.7 ± 2.3 MPa in the ulnar component, 5.4 ± 1.7 MPa in the dorsal component, 6.1 ± 3.3 MPa in the fibers of the fovea, and 8.1 ± 1.2 MPa in the articular disc.
Conclusions: The Young's modulus of each component was about 5 to 9 MPa. Specimens used in this study were from elderly individuals, and care must be taken when using these values for FEM.
Clinical relevance: These data will be used to perform FEM to predict the mechanical behavior of the ulnar side of the wrist and the stress distribution applied to the TFCC, the distal radioulnar joint, and the ulnar head.

Triangular fibrocartilage complex (TFCC) injury is a frequently encountered cause of ulnar-sided wrist pain. This injury is broadly classified into traumatic and degenerative lesions.[1] Degenerative tears in the articular disk component of the TFCC are frequently attributed to ulnar impaction syndrome, which implies that excessive and chronic compressive loading across the ulnocarpal joint are the primary mechanical factor responsible for these tears.[2] In contrast, a tensile force caused by distraction of the distal radioulnar joint (DRUJ) has been implicated as an important mechanism for traumatic tears.

Since Palmer and Werner's[2] publication in 1981, there have been many reports on the anatomy and function of the TFCC. The TFCC is a compound structure composed of the articular disc, proximal and distal laminae, volar and dorsal radioulnar ligaments, ulnolunate ligament, ulnotriquetral ligaments, ulnocollateral ligament, sheath of the extensor carpi ulnaris (ECU) tendon, meniscus homologue, and capsule.[2] The TFCC stabilizes the DRUJ by acting as a cushion for the ulnar head and lunate during axial loading and ulnar deviation of the wrist.[2] It also limits ulnar deviation of the carpus.[2] There is still great debate about the function of the structures within the TFCC. For instance, it is not known which of the dorsal and volar fibers of the radioulnar ligament are in tension with pronation or supination of the forearm (the Schuind–Ekenstam paradox,[3,4] Nakamura and Makita[5] described the 3-dimensional structure of the TFCC as a hammock-like structure.

To clarify the function and pathology of the TFCC, it is important to know the biomechanical behavior of the TFCC. Makita et al[6] studied changes in the shape of the TFCC that occur during forearm rotation. Nishiwaki et al[7] examined changes in the stabilizing effect of the ulnar-shortening procedure and pressure at the DRUJ of that procedure.[8] However, in cadaveric studies, it is impossible to know the stress distribution of the TFCC.

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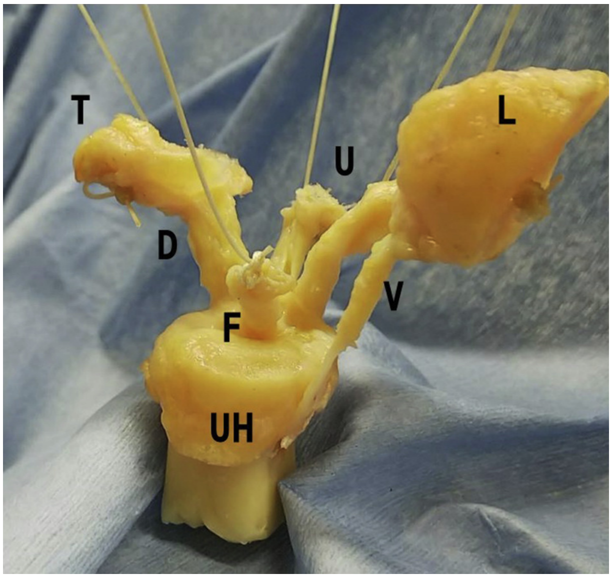

Figure 1. Each component after dissection. D, dorsal side; F, fibers of fovea; L, lunate; T, triquetrum; U, ulnar side; UH, ulnar head; V, volar side.

Finite element analysis (FEA) can be used to investigate stress distribution within the TFCC, but its accuracy depends on understanding the material properties of the TFCC. To our knowledge, there is only one report about the material properties of the articular disc of the TFCC,[9] and there are no detailed reports about the material properties of each component of the TFCC. The aim of this study was to evaluate the material properties of the TFCC using cadaveric specimens to predict the stress distribution applied to the TFCC, the DRUJ, and the ulnar head by FEA.

Materials and Methods

Specimens

We obtained 12 upper limbs (6 right and 6 left) from 6 fresh-frozen cadavers (3 women and 3 men) from the Clinical Anatomy Laboratory in our university. Average age was 78.3 years (range, 69–87 years). The donors had no history of surgery around the wrist or trauma. We stored all specimens at −20°C and thawed them at room temperature for 24 hours before conducting the experiments. A saline solution spray was periodically used to keep the specimens moist during all procedures.

Dissection

A 20-cm skin incision, centered over the DRUJ, was made between the fourth and fifth extensor compartments. The extensor digiti minimi and ECU sheathes were opened and the tendons were retracted. A transverse ulnar osteotomy was made 3 cm proximally from the ulnar styloid. A radial osteotomy was performed on the ulnar side of Lister tubercle. The lunate and triquetrum were removed while leaving the soft tissues with the distal ulna. We dissected 5 components (the dorsal, volar, and ulnar sides, the articular disc, and the fibers of the fovea) from this excised DRUJ. The dorsal side included the sheath of the ECU and the capsule. The volar side included the ulnolunate ligament, the ulnotriquetrum ligament, and the capsule. The ulnar side included the ulnocollateral ligament and the ulnomeniscal homolog. The carpals were separated so that the attachment part of each component was included (Fig. 1).

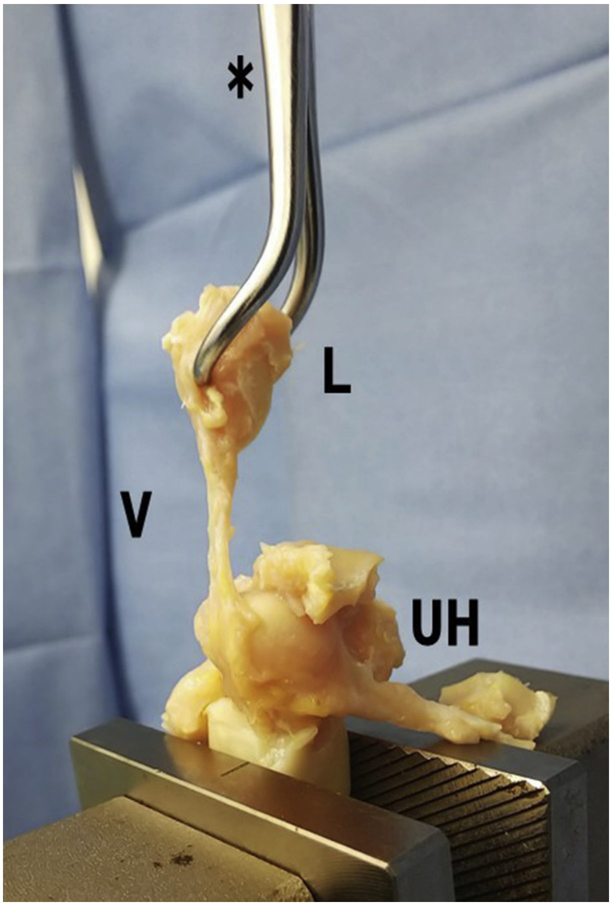

Figure 2. Tensile testing of volar side. *Bone grasping forceps; L, lunate; UH, ulnar head; V, volar side.

Tensile testing

Components without the articular disc were subjected to a single loading test using a mechanical testing machine (AG-Xplus, Shimadzu, Kyoto, Japan). To clamp firmly, the ulna was fixed with resin. The distal end of the specimens was clamped with grasping forceps (Fig. 2). The length of the specimen was measured with a digital caliper (model 19974, Shinwa Rules Co, Ltd, Niigata, Japan) and the circumference of the specimen was measured using 5-0 nylon suture. Then, these were used to calculate the approximate sectional area of the specimens.

All components were prepared with a preload of 2 N before applying a tensile load at 5 mm/min using a 500 N load cell. We obtained the force–displacement curve and converted this into a stress–strain curve using the length and sectional area of the specimens. Young's modulus was calculated from the slope of the linear part of the stress–strain curve.

Compression testing

The articular disc was subjected to compression testing at room temperature using the same testing machine employed for the tensile tests. The length and sectional area of the specimen were measured in the same way as for tensile testing.

The specimen was prepared with a preload of 2 N before applying a compression load at 2 mm/min using a 500 N load cell. Young's modulus was calculated in the same way as for tensile testing.

Table 1
Results of Tensile Testing

Variable	Length, mm	Sectional Area, mm^2	Young's Modulus, MPa
Volar component (mean ± SD)	16.6 ± 3.5	8.1 ± 2.7	7.0 ± 2.4
Ulnar component (mean ± SD)	15.2 ± 3.4	7.6 ± 2.6	8.7 ± 2.3
Dorsal component (mean ± SD)	16.0 ± 4.3	8.8 ± 2.9	5.4 ± 1.7
Fibers of fovea (mean ± SD)	8.5 ± 1.7	13.3 ± 3.7	6.1 ± 3.3

Results

Tensile testing

Table 1 lists data for the lengths, sectional areas, and Young's modulus of tissues from each component of the TFCC.

Compression testing

The thickness of the articular disc was 3.5 ± 0.6 mm (range, 2.9−4.6 mm), the sectional area was 21.2 ± 3.9 mm^2 (range, 13.9−29.5 mm^2), and the Young's modulus was 8.1 ± 1.2 MPa (range, 6.5−10 MPa).

Discussion

We investigated the material properties of the TFCC using fresh-frozen cadavers. Young's modulus was 7.0 ± 2.4 MPa in the volar component, 8.7 ± 2.3 MPa in the ulnar component, 5.4 ± 1.7 MPa in the dorsal component, 6.1 ± 3.3 MPa in the fibers of the fovea, and 8.1 ± 1.2 MPa in the articular disc.

It is most accurate to use fresh-frozen cadavers to measure tissue material properties. Chemically preserved tendons (Thiel method or formalin-fixed) are notably stiffer in tension than fresh-frozen specimens.[10] Huang et al[11] showed that repetitive freezing−thawing (below 5 cycles) did not degrade the structural, mechanical, and viscoelastic properties of human tendons. In this study, the material was frozen and thawed less than 3 times.

There is no detailed information in the literature about the material properties of tissues in the TFCC. The only report about tissue properties of the TFCC used indentation testing of the articular disc and reported an indentation modulus of normal articular disc of 10.1 ± 3.7 kPa.[9] This is low compared with our result (7.84 ± 2.45 MPa). However, our techniques were different because indentation testing measures small areas and is point-specific, whereas our method of testing measures a larger area of the disc and is not subject to local variations in tissue properties. Therefore, our measurement may be more clinically relevant. In addition, the articular cartilage and meniscus, which are histologically similar to the articular disc (mainly type 2 collagen fibers), have a Young's modulus of 5 to 10 MPa,[12−15] similar to our results for the articular disc.

We performed a mechanical test for each component of the TFCC. The specimens included bone−ligament−bone and ulnar bone−ligament samples. To clamp firmly, the ulna was fixed with resin and the distal end of the specimens was clamped with grasping forceps, either bone-grasping forceps for bone−ligament−bone samples or tendon-grasping forceps for ulnar bone−ligament samples. There was no failure resulting from displacement at these fixed parts.

There are various methods for immobilizing specimens for tensile ligament testing,[16−18] but no conclusion has been drawn as to which method is most appropriate. Differences in fixation methods may affect measurement of the failure load,[19] but because the failure load was not investigated in this study, it is unlikely that the method of grasping affected the results.

In this study, the loading rate was set at 5 mm/min based on our previous experience. Because the specimen was small, slippage at the grips will occur if loading is too fast. Because of viscoelastic effects, the loading rate will affect the Young's modulus.[19] The effect of the loading rate on properties of tissues in the TFCC should be further examined.

In our study, the specimens were from older individuals. Noyes and Grood[20] tested young and old anterior cruciate bone−ligament−bone material properties. They found a reduction in stiffness (129 vs 182 N/mm), failure load (734.0 vs 1730.0 N), elastic modulus (65.3 vs 111.0 MPa), maximum stress (13.3 vs 37.8 MPa), and strain (30.0% vs 44.3%) when comparing older and younger samples, respectively. In the patella tendon, which has the same collagen component as the anterior cruciate ligament, there is a report that older people had lower tensile strength (53.6 ± 10.0 vs 64.7 ± 15.0 MPa) and Young's modulus (504 ± 222 vs 660 ± 266 MPa).[21] On the other hand, it was reported that in the articular cartilage of the knee, the influence of osteoarthritis changes is larger than the effects of age.[22] It is well-documented that material properties change during aging[23]; therefore, the age and perhaps other demographic characteristics of cadavers will greatly influence material property data. However, cadaveric studies of the TFCC are limited and it is difficult to compare older and younger specimens.

This study had several limitations. The most important is that all cadavers were from elderly subjects. As mentioned, the Young's modulus may be lower in elderly people compared with younger ones. In clinical practice, TFCC injury is common at a young age, and it may be more relevant to evaluate the form of damage and the force to injury in younger specimens. However, it is useful to investigate trends clarifying where stress concentrates during forearm rotation and in which limb position stress is more concentrated. Thus, FEA as was employed in this study can be useful in investigating material properties. Second, we performed only uniaxial tensile tests. The TFCC is exposed not only to stress in the major axis direction but also to rotational stress. In this study, it was impossible to study rotational stress. Third, in soft tissues such as tendons and ligaments, the length and cross-sectional area of the specimen affect the Young's modulus.[24] It can be difficult to dissect specimens from precisely comparable areas of the TFCC, and this may create some variability among specimens.

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