The Effects of Elbow Joint Angle on the Mechanical Properties of the Common Extensor Tendon of the Humeral Epicondyle

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The purpose of this study was to determine the effects of elbow joint angle on mechanical properties, as represented by ultimate load, failure strain and elastic modulus, of bone-tendon specimens of common extensor tendon of the humeral epicondyle. Eight pairs of specimens were equally divided into two groups of 8 each, which selected arbitrarily from left or right side of each pair, positioned at 45° and 90° of elbow flexion and subjected to tension to failure in the physiological direction of the common extensor tendon. For comparison of the differences in the failure and elastic modulus between tendon and the bone-junction, data for both were evaluated individually. Significant reduction in ultimate load of bone-tendon specimens was shown to occur at 45°. The values obtained from the bone-tendon junctions with regard to the failure strain were significant higher than those from tendon in both loading directions, but the largest failure strain at the bone-tendon junction was found at 45°. The elastic modulus was found to decrease significantly at the bone-tendon junction when the loading direction switched from 90° to 45°. Histological observation, after mechanical tensile tests, in both loading directions showed that failure occurred at the interface between tendon and uncalcified fibrocartilage in the thinnest fibrocartilage zone of the bone-tendon junction. We concluded that differences in measured mechanical properties are a consequence of varying the loading direction of the tendon across the bone-tendon specimen.

Key Words : Mechanical Properties, Common Extensor Tendon, Histological Observation, Fibrocartilage

1. Introduction

Based on epidemiological studies of manual work activities, individuals at high risk for upper limb tendinitis of the overuse nature include all those who place a repeated stress on the flexors and extensors of forearm, such as fishermen, assembly line workers, craftsmen, tennis players, and golfers (Bureau of Labor statistics, 1990). Common extensor tendon of the humeral epicondyle, like other tissues, is subject to damage from a variety of sources including direct blows and excessive tensile forces (Curwin et al., 1984). Biomechanical studies have demonstrated that forceful exertions can produce stress concentrations on tendons adjacent tissues that correspond with the sites of injury (Armstrong et al., 1979a ; Catelli et al., 1980). Mechanically induced injuries in bone-tendon unit can be categorized into tow categories: acute trauma as a result of immediate tissue overload and chronic damage as a result of low-level but repetitive or prolonged loading (Glazebrook et al., 1990).

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In recent years, many researchers have studied the mechanical properties of tendon, ligament, and bone-ligament-bone complex, such as femur-ACL-tibia and FATC in human and animals because of their functional importance and high incidence of injury (Butler et al., 1984; Dorlot et al., 1980 ; Graf et al., 1992 ; Haut et al., 1988 ; Johnso et al., 1994 ; Lyon et al., 1989). Although soft tissue from various anatomical sites have been studied extensively, very little information is available about the biomechanical properties of bone-tendon specimens of the common extensor tendons of the humeral epicondyle, partly due to the difficulties in procuring young and healthy cadaveric specimens. In addition, its complicated structure is difficult to evaluate mechanically. Our laboratory has recently developed an experimental device whereby the human elbow specimens can be oriented and tested at any desired loading direction. Han and his associates (1994), in our lab, performed tensile tests of bone-tendon specimens of human cadaver elbow and their results showed that 1) tensile failure could at the bone-tendon junction through mechanical testing at a loading direction of 45° (elbow in flexion) and the weakest point of the bone-tendon unit of the lateral epicondyle was the transitional zone between bone and tendon.

This present study was undertaken to evaluate the effect of the direction of applied load on the mechanical properties, such as ultimate load, failure strain, and elastic modulus, of bone-tendon specimens of the humeral epicondyle. In past, some published works have demonstrated that the direction of applied force influences the mechanical properties of bone-ligament-bone specimens. Figgie et al. (1986) showed that significant differences occurred in ultimate loads, deflection and energy absorbed when canine femur-ACL-tibia complexes were subjected to tensile tests with axial tibia orientation and 0°, 45° and 90° of femoral orientation with respect to load direction. Woo et al. (1988) described a significant change in structural properties of the rabbit femur-ACL-tibia complex when load was applied along the longitudinal axis of the ligament instead of along the longitudinal axis of the tibia. Similar results were found in human ACL specimens by Hollis et al. (1987). However, they did not addressed forces on the bone-ligament insertion site, because failures resulted in either bone avulsion when the load was applied along the ACL axis or ligament rupture when loading was along the axis of the tibia.

Based on findings that the mechanical properties of the bone-tendon unit or bone-ligament-bone unit are influenced by the direction and patterns of applied loads (Gupta et al., 1971 ; Alm et al., 1974 ; Woo et al., 1986 ; Figgie et al., 1985 ; Han et al., 1994), we hypothesized that different directions of load application would result in different mechanical responses in the bone-tendon specimen of humeral epicondyle. To examine this hypothesis, experimental force-deformation data were obtained when loaded to failure in various directions. Form these data values were determined for ultimate load, failure strain, and elastic modulus for the bone-tendon specimens of the humeral epicondyle.

2. Material and Methods

2.1 Specimen preparation

Eight pairs of fresh frozen human (6 male and 2 female) cadaver elbow specimens underwent mechanical tensile testing. Information about the dominant or non-dominant sides of the paired specimens was not available. Age of the specimens ranged was 71 ± 9.5 (Table 1). The cadaver specimens were wrapped in saline soaked gauze, double wrapped in plastic bags and stored at −15℃. Before testing, a specimen was removed from the walk-in freezer and thoroughly thawed at room temperature. Anterior-posterior and lateral roentgenograms excluded specimens with any bony abnormality. All excessive muscles, except the common extensor and origin of the epicondyle, were removed. Approximately 50-60 mm of the common extensor tendon, distally from its origin, remained after dissection. Cross-sectional area of the bone-tendon specimens of the common extensor tendons at 5 mm distal from the origin was measured by the area micrometer technique (Ellis, 1969 ; Bechtold et al., 1994)

Table 1 Information of Cadaver Specimen Used in this Study

Subject	Sex	Age	Cause of Death
1	F	64	Heart Attack
2	F	60	Pneumonia
3	M	78	Natural Death
4	M	82	Traffic Accident
5	M	76	Diabetes
6	M	58	Gun Shot
7	M	84	Natural Death
8	M	66	Pneumonia
Mean (STD)		71 (9.5)	

before testing using 0.1 MPa compression for measurement. A custom-designed grip device held the tendon 15 mm distal to its origin at the humeral epicondyle. The grip device was placed into the test fixture, which was attached to the MTS machine, with the distal part of the tendon at the selected angle of flexion. The loading fixture was oriented such that the direction of loading was along the anatomical position of elbow flexion. Specimens were kept most with saline throughout preparation and testing. The mechanical experiments were performed at room temperature.

2.2 Experimental apparatus

Mechanical tests were performed on an electro-hydraulic materials testing machine where located in Orthopedic Research Laboratory of Texas Tech. University. Prepared specimens were mounted with bone cement in an electrical conduit 40 mm in diameter. Specially designed devices attached to the MTS machine made it possible to change the elbow angle, which we adjusted to 90° and 45°. For the tensile tests, load and displacement were monitored with a load cell and a linear variable displacement transducer (LVDT), respectively. Two strain gauges were attached to the surface of the bone near the junction in the direction of loading to obtain the strain in the bone during testing. Data for ultimate load from the bone-tendon specimen and strain from strain gauges on the bone surface were collected and analyzed by a computer.

Strain measurements in tendon and the bone-tendon junction were carried out with steel pins. To measure the distances between pins, an imaging system of Optimas manufactured by Edmonds, WA was used, which includes a JVC KY-F30B 3-CCD color camera, an Olympus BH-2 with bright and dark field illumination and a Dell 90 MHX pentium computer with a Matrox MVP AT image capture board. It automatically identifies points, lines and distances of and between the pins. The data was read and transferred to Excel.

Data were analyzed using a two-way analysis of variance (ANOVA) to determine any statistically significant difference in ultimate load, failure strain, and elastic modulus due to varied loading directions and anatomic sites (tendon versus the bone-tendon junction). Significance was set at $p<0.05$.

2.3 Experimental procedure

Each pair of specimens were loaded in physiological direction of the common extensor tendons of 45° at one side and 90° at another side. The specimen was stretched to failure at a displacement rate of 12 mm min^{-1}.

For histological observation and measurement, the common extensor origins of two paired failure cadaver specimens (after tensile tests) were harvested. A block, 10 mm × 10 mm × 5 mm, was taken from the junction unit, decalcified with nitric acid and embedded in paraffin wax. Several sections were cut on a microtome at 8 μm thickness along the long axis of the tendon and at right angles to the bone surface. The sections were stained with Masson-trichrome, from which it is easy to distinguish fibrocartilage from bone and tendon by colors. The thickness of fibrocartilage was estimated in both the anterior and posterior aspects of the bone-tendon junction under microscope (Han et al., 1994).

We divided specimens with steel pins (0.7 mm) into three parts-tendon, bone-tendon junction and bone-tendon complex-and measured displacement changes in each part (Fig. 1). The pins, which penetrated into the tendon sheath between fibers, did not damage the tendon fibers

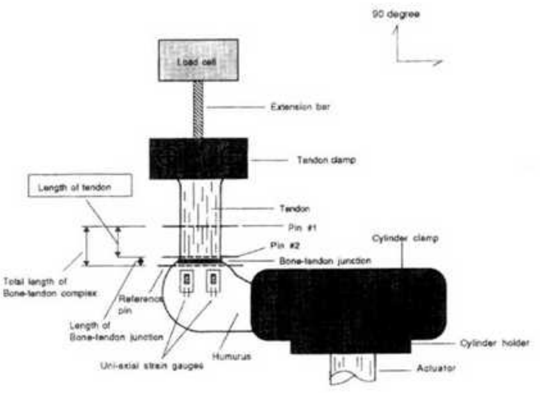

Fig. 1 Sketch shows the bone-tendon specimen during a tensile test

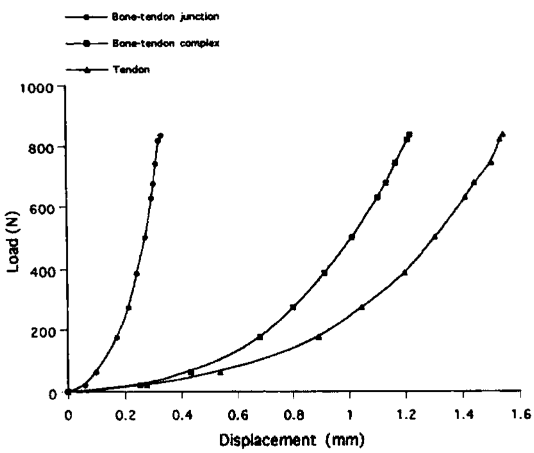

Fig. 2 Plot of load against displacement for tendon, bone-tendon complex and bone-tendon junction. Test was performed at 45° and 12 mm min^{-1} of displacement rate

(Wang et al., 1995). Pin 1 penetrated through the tendon in the lower middle region parallel to the surface of the bone-tendon junction. Pin 2 penetrated into the tendon as close to the surface of the junction as possible so we could have the best estimation of strain change in the junction (including uncalacified and calcified fibrocartilage). A reference pin was penetrated into the bone very near the bone-tendon junction and parallel to the other pins to determine the initial length between pins. The distance between the reference pin and the pin 2 was 3 to 4 mm. This distance included a length of tendon, bone and the total thickness of the bone-tendon junction. We photographed the pins in the specimen at intervals during loading; exposure times were recorded by computer. Accurate changes in displacements between pins were measured with the imaging system from a series of photo slides. The displacements between pins were measured with the imaging system from a series of photo slides. The displacements between pins were measured from the middle points of pins. A typical load vs deformation curve for a load to failure test of bone-tendon specimen was derived (Fig. 2). Strain in tendon, bone-tendon complex and at the bone-tendon junction was obtained by using the displacements between pins to divide the initial distance between pins. The strain in the tendon was measured between pin 1 and pin 2 and in the bone-tendon complex between pin 1 and the reference pin. We defined the strain between pin 2 and the reference pin as an approximate strain in the bone-tendon junction.

Load is plotted against displacement so gradients represent stiffness. To allow for the different cross-sectional areas and distances between pins of the specimens, we plotted stress against strain rather than load against displacement. The linear part of the slope of the stress-strain plot was the elastic modulus. The cross-sectional area of tendon, which was measured near the bone-tendon junction, was applied to the bone-tendon junction.

3. Results

Load-deformation curves for the paired specimens obtained from the failure tests (Fig. 3(a)). These curves can also be expressed in terms of the stress-strain relationship, since the cross-sectional area is known. The general tensile behavior of the bone-tendon specimen is nonlinear. The initial and toe portion of the stress-strain curves are characterized by low modulus (i.e., relatively large increase in strain with a small increase in stress). The intermediate region is characterized by linear elastic modulus. Finally, at the yield region, the modulus decreases as the specimens begin to fail successively before

Table 2 Results of mechanical tensile test in tendon and at the bone-tendon junction with a displacement rate of 12 mm/min

Elbow in Flexion (degrees)	Samples of Specimens	Number (n)	Cross-sectional area	Ultimate load (N)	Failure strain	Stress (MPa)	Elastic modulus (Gpa)
45	Bone-tendon junction	8	*61.43±11.37	764±145	0.0942±0.034	12.5±3.5	0.168±0.116
45	Tendon	8	61.43±11.37	—	0.0701±0.023	—	0.194±0.106
90	Bone-tendon junction	8	*64.97±13.48	667±103	0.158±0.026	10.3±1.7	0.085±0.035
90	Tendon	8	64.97±13.48	—	0.075±0.032	—	0.167±0.098

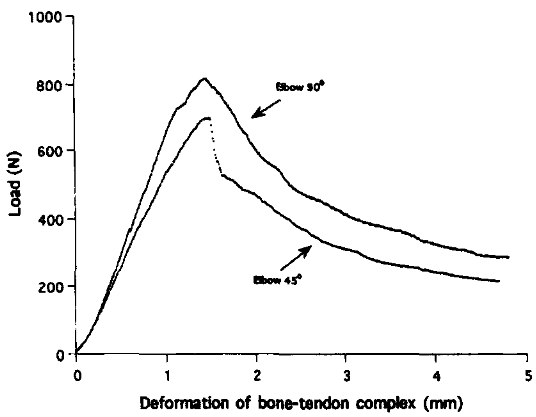

Fig. 3(a) Typical load vs deformation curves of load to failure tests of bone-tendon specimens at different degrees of elbow flexion

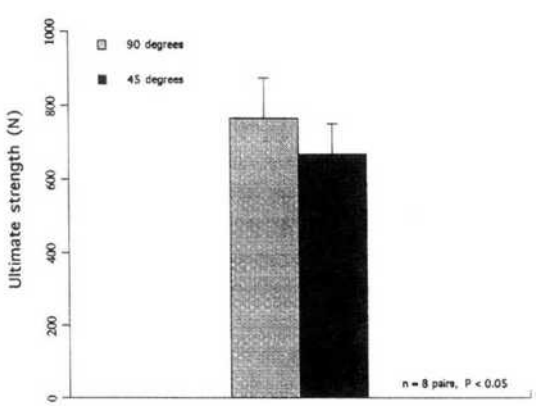

Fig. 3(b) Ultimate load of the bone-tendon specimens at different degrees of loading. Statistical analysis (Two-way ANOVA test) revealed that a significant difference in ultimate load was found between 45° and 90° of loading ($p<0.05$)

complete failure.

The results of the ultimate load for the load to failure tests on the bone-tendon specimens are summarized in Table 2 and Fig. 3(b). When the 8 paired specimens were evaluated, two-way ANOVA revealed that a significant differences in ultimate load was found between 45° of loading (667±103 N) and 90° of loading (764±145 N), ($p<0.05$).

In comparing stress-strains curves obtained directly in tendon and at the bone-tendon junction with strains based on pin-to-pin measurements (Fig. 4 and Fig. 5). Statistical analysis using a two-way ANOVA revealed that there are significant differences in strains of tendon and the bone-tendon junction at both 45° and 90° ($p<0.05$). The strains at both loading directions occurred at the bone-tendon junction were significantly larger than the average strain in tendon by a factor of one-half to almost two. Comparison of the failure strains of the bone-tendon junction at the ultimate load in our tensile tests showed that largest failure strain (0.158±0.026) produced at 45°, being 1.7 times the failure strain at 90° (0.0942±0.034) [statistically significant ($p<0.05$)] (Fig. 6). However, no significant difference was found in strain for tendon tested at both loading directions. Strains in bone measured by the strain gauges were small (0.0002±0.0001).

Figure 7 showed that the elastic modulus for tendon and bone-tendon junction were 0.167±0.098 Gpa and 0.085±0.035 Gpa at 45° of loading, 0.194±0.106 Gpa and 0.168±0.116 Gpa at 90° of loading. A significant difference in elastic

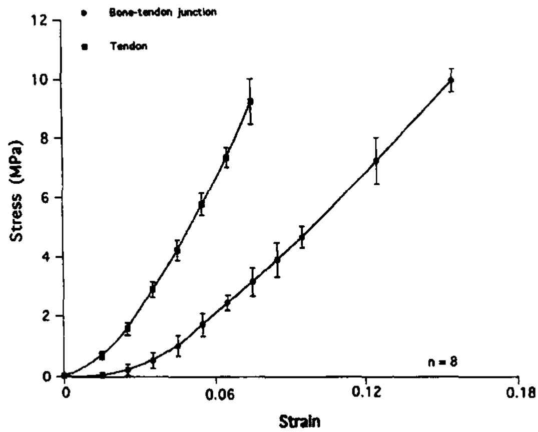

Fig. 4 Engineering stress-strain curves of tendon and bone-tendon junction at 45° of loading. Statistical analysis (Two-way ANOVA test) revealed that there are significant differences in strains of tendon and bone-tendon junction ($p<0.05$)

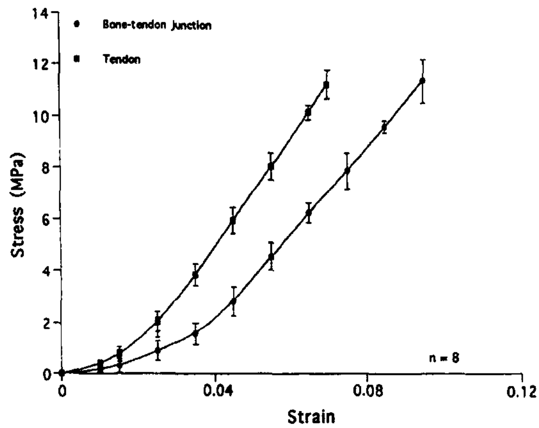

Fig. 6 Engineering stress-strain curves of tendon and bone-tendon junction at 90° of loading. Statistical analysis (Two-way ANOVA test) revealed that there are significant differences in strains of tendon and bone-tendon junction ($P<0.05$)

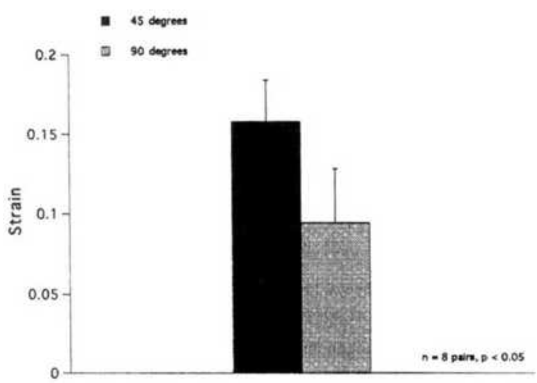

Fig. 5 Comparison of the failure strains of the bone-tendon junction at the ultimate load in tensile tests. The largest failure strain occurred at 45°, being 1.7 times the failure strain at 90°

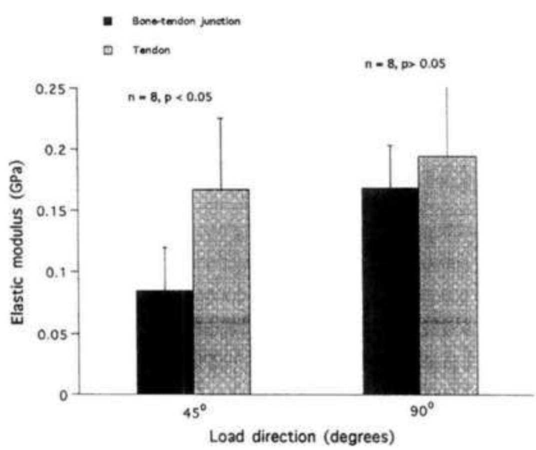

Fig. 7 Elastic modulus representing initial linear part of slope of stress-strain curve were measured for tendon and bone-tendon junction at 45° and 90° of loading. A significant difference in elastic modulus was noted using a two-way ANOVA for tendon and the bone-tendon junction at 45° ($p<0.05$). But no significant difference was found between tendon and bone-tendon junction at 90° ($p>0.05$)

modulus was noted using a two-way ANOVA for tendon and bone-tendon junction at 45° ($p<0.05$). But no significant difference was found between tendon and bone-tendon junction at 90° of loading ($p>0.05$).

In the paired study, the ultimate load, failure strain and elastic modulus for the bone-tendon junction and tendon at 45° and 90° of loading are detailed in Table 2.

Histological observation demonstrated that the specimens failed at the bone-tendon junction at both 45° and 90° of loading and that breakage occurred at the interface between tendon fibers

Fig. 8 Histological observation demonstrated that the specimens failed at the bone-tendon junction at both 45° and 90° of loading and the breakage occurred at the interface between tendon fibers and uncalcified fibrocartilage

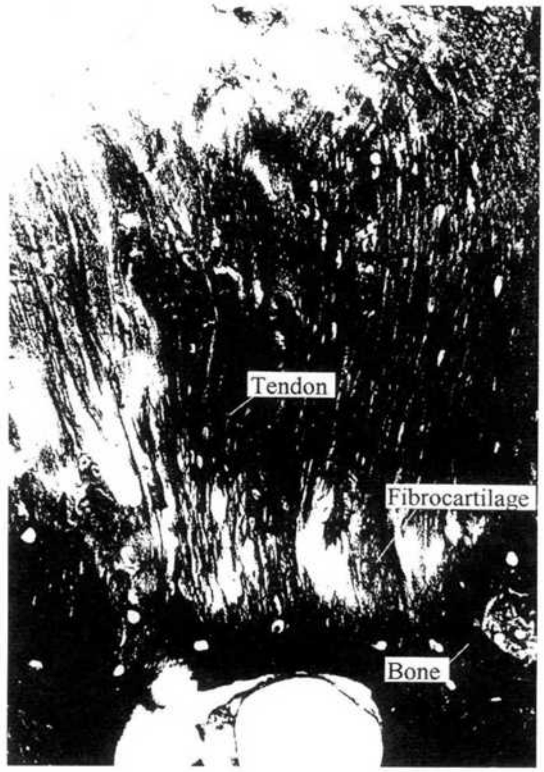

Fig. 9 Details of failure at the bone-tendon junction could be seen in fibrocartilage which the collagen fibers were pulled from the fibrocartilage and part of the fibrocartilage was split

and uncalcified fibrocartilage mostly at the anterior aspect of the bone-tendon junction (Fig. 8). Some damage could be seen in the fibrocartilage (Fig. 9) which looked as if the collagen fibers were pulled from the fiberocartilage or part of the fibrocartilage was split.

4. Discussion

In this study, our histological observations has been clearly demonstrated that tensile failure occurred at the bone-tendon junction at both 45° and 90° of loading directions. In general, true bone-tendon junction failure are not very common. Probably the most common is the midsubstance rupture or bone avulsion in bone-tendon specimens (Viidik, 1973). However, past studies have showed that ligaments and tendon could fail through their junctions (Tipton, et al., 1976; Noyes, et al., 1974). Tipton and associates found that more than 70% of all ligament-bone, with the remaining 30% beginning in the nonmineralized fibrocartilage or the in the ligament near the junction. The failure modes of bone-tendon specimen or ligament-bone specimen may relate to the testing conditions including displacement rate and age. Crowninshield, et al.(1976) found that the mode of failure in rat FMT complex depended on the extension rate. On the other hand, Peterson, et al.(1986), demonstrated that the age of the animal had a more significant effect on the mode of failure than does the extension rate. Our specimens ages arranged from 58 to 84. The age effect should be identified when young specimens are available in the future.

Our results showed that a higher ultimate load was found at 90° of loading direction than at

45°. Tendon fibers generally insert into bone at acute angles ; that is, the angle between the fibers and bone surface (Benjamin et al., 1986). Thus the tensile forces in tendon can produce both tension and shear forces at the bone-tendon junction (Woo et al., 1988). The influence of the ultimate load in the bone-tendon specimen is that a change of loading direction might result in a change of the proportion between tension and shear forces at the bone-tendon junction.

We measured strains in tendon and at the bone-tendon junction by pins because we have not found it possible to prevent tissue slippage while directly gripping soft tissue. In past, many measurements of strain in tendon or bone-tendon specimen might be subject to a large experimental error because the slippage of soft tissue in grips (Ker, 1981). Although it is possible to secure one end by means of its bony insertion, the other end must gripped in some kinds of grips. Thus we have greater confidence in the data base on pins measurements in tendon. Although the method used in our experiments is the one of many better ways in measuring strain at the bone-tendon junction, the data were still subject to a error because pins could not be placed close enough to the edges of the junction. So far, there is no an accurate way to measure strain at the bone-tendon junction because the fibrocartilage is very thin and irregular in shape.

The greatest strain was found at the bone-tendon junction in both loading directions, which is similar to findings from other authors (Woo et al., 1983 ; Noyes et al., 1984 ; Bulter et al., 1984). The failure strain in the bone-tendon junction at 90° loading direction was 40% less than in the 45° loading direction. There was only 15% more failure strain in the bone-tendon junction than in the tendon at 90° loading direction but failure strain was about two fold higher at the bone-tendon junction than in the tendon when the loading direction was changed to 45°.

The elastic modulus at the bone-tendon junction is significant lower than in tendon when load applied at 45°. But, no significant difference in elastic modulus was found between them at a loading direction of 90°. This also indicated that the proportion between tension and shear forces at the bone-tendon junction is changed with loading direction because the shear modulus is different from tension modulus in fibrocartilage (Currey, 1984).

As evidenced by the results obtained in this study, the direction of applied tensile load should be a very important parameter to consider when investigating the biomechanical properties of the bone-tendon unit of the epicondyle. Cartilage or fibrocartilage is an anisotropic material and has different mechanical responses to load patterns including tension and shear forces (Woo et al., 1976 ; Kempson, 1979 ; Roth et al., 1980 ; Currey, 1984). Therefore, the differences in measured ultimate load, failure strain and elastic modulus are a consequence of varying the loading direction of the tendon across the fibrocartilage in the bone-tendon junction. In other words, the direction of the applied force influences the force patterns on the fibrocartilage so the mechanical properties of fibrocartilage may be changed. In future studies, we expect to investigate the mechanical response to a series of elbow angles in flexion. The method of strain measurement used in this study is one of many possible ways to examine the bone-tendon unit, but it cannot show the strain in fibrocartilage without the effects of tendon and bone and the strain distribution in different location of the bone-tendon junction. It expect that a new method or a new device will be designed to measure strain accurately.

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