Tendon Responses Depending on Different Anatomical Locations

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The objectives of this work focus on the differences in responses of paired tendons from different anatomical locations. Tendon specimens were obtained from the hindlimbs of canines and frozen to −70℃. After being thawed, specimens were mounted in the immersion bath, preloaded to 0.13 N, and then subjected to 3% or 4% of the initial length at a strain rate of 5%/sec. It was found that the mechanical responses of anatomically paired tendons were nearly the same within each pair but different between pairs of tendons from different anatomical locations. Although flexor tendons had much larger cross-sectional area than the others, such as peroneus or extensor tendons, the stiffness of the flexor tendons were much lower than the others throughout their stress-strain responses. The nature and causes of these differences in the stiffness are not fully known. However, it is clear that differences in the mechanical response of tendons and other connective tissues are significant to the musculoskeletal performance.

Key Words : Tendon, Stress-Strain Response, Anatomically Paired, Difference, Musculoskeletal Performance, Connective Tissue

1. Introduction

Tendons are collagenous tissues which connect muscles to bones, and those remain rather inextensible relative to the motions in muscle during contraction. Morphologically, the tendon is a complex material consisting primarily of collagen fibers with a small percentage of elastic fibers and a matrix of the ground substance (Elliot, 1965). The main function of tendon is to transmit force between muscle and bone.

There exists greater non-linearity for the stress-strain curve for flexor tendon than that for the extensor tendon (Benedict et al., 1968). Flexor tendons inherently has high strength (Woo et al., 1980; Woo et al., 1981; Woo, 1986). They also reported the higher collagen concentration for the flexor tendon than for the extensor tendon. Fresh human ligaments and tendons were tested for the different anatomical locations (Berg et al., 1983). They showed that the flexor tendon has lower maximum tensile strength and elastic modulus than the extensor and peroneus tendons. Rhesus knee ligaments vary in modulus, ultimate stress, and rupture stress for different locations in the same joint (Grood et al., 1977). The material properties vary from location to location for human patellar tendons and knee ligaments in the same knee, and those also vary for different knee ligaments and patellar tendons (Butler et al., 1986). The relaxation response of anatomically paired tendons is generally similar, while that of not-paired tendons is different (Chun and Hubbard, 1986).

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2. Materials and Methods

Tendon specimens were obtained from the hindlimbs of canines which had been sacrificed in veterinary surgery classes. Within an hour post-mortem, the whole limbs were refrigerated at near freezing, and tendons were dissected within one day.

After dissection, each paired tendon specimen was wrapped in Ringer's lactate soaked paper towel and sealed in small plastic bags labelled with the name of anatomical location and the date of dissection. Thereafter, groups of paired tendons from each canine were put into a larger plastic bag, put into an air-tight container, and stored in a freezer at −70℃. This packing method (Chun and Hubbard, 1986 ; Chun and Hubbard, 2001a ; Chun and Hubbard, 2001b) prevents tendon from dehydration and decay during storage. Each specimen is 45 mm or longer with the almost near constant cross-sectional area. Thick specimens with the major diameter larger than 3 mm and the minor diameter smaller than 1 mm were discarded, because it was thought that large cross-sections would not insure the uniform pressure between interior and exterior fibers during gripping.

At the beginning of each test, a tendon specimen was soaked in the Ringer's lactate solution for a minimum of 30 minutes for complete thawing. Tests were conducted using a computer controlled and the servo-hydraulic Instron testing system (Model, 1331) with its hydraulic cylinder in the upper crosshead. To grip a tendon specimen, flat-plate clamp type grips were employed with waterproof 100 grit silicon carbide abrasive paper in the inner surface. At both ends, the side of the specimens were marked with a water resistant pen, and these marks were placed just inside the edges of the grips. These marks were observed and photographed with a WILD MPS 55 stereo-microscope during the extension. The marks were not detected by the microscope shown by photographs, indicating that no detectable slippage accurs in this gripping method (Chun and Hubbard, 1986 ; Chun and Hubbard, 2001a ; Chun and Hubbard, 2001b).

Histological examinations showed that the tendon fibers within the grips were continuous and compressed together, but those were neither torn nor fractured.

Grip motion was measured with an LVDT mounted in the hydraulic actuator of the Instron testing machine. The load was measured with a fully submersible interface load cell (Model SSM-A5-100) which has a maximum 444.82 N load and was mounted in the immersion bath. The initial length of the specimen between grips was measured by a micrometer with an accuracy of 0.01 mm at a preload of 0.13 N on the specimen. During the taet, the specimen was immersed in a Ringer's lactate bath at room temperature (22℃).

As in our previous studies (Chun and Hubbard, 1986 ; Chun and Hubbard, 2001a ; Chun and Hubbard, 2001b), the cross-sectional area of the specimen was measured from histological cross-sections prepared with commonly used paraffin embedding. The slides with the cross-sections were placed in a photographic enlarger with a precision scale and photographs were taken. From these photographs, the compact collagen bundle cross-section was selected and measured using a Numonics digitizer which has the accuracy within 0.01 mm^2.

A PDP-11/23 computer was used for test control and data acquisition, storage, and analysis. An Instron Machine Interface Unit and an Instron Machine Driver enable command and communication between the computer and the testing machine. Data were also monitored and stored on a Nicolet digital oscillosope (Model 201, series 2090).

Peak strain levels of 3% and 4% were chosen to study the strain level and the sequence sensitivity. These strain levels were selected to be in the physiological range and below the level for significant damage. A constant strain rate of 5%/sec was chosen in loading and unloading tests as an intermediate rate between rapid and slow physiological movements.

The test number, anatomical location, tendons status (pair), cross-sectional area, initial length, and peak load (N) for each tendon specimen

Table 1 Tendon specimen characteristics

Test No	Anatomical Location	Tendon Status	Initial Length (mm)	Area (mm^2)	Peak Load (N)
1	Peroneus longus	pair	32.54	0.58	18.23
2	Peroneus longus		32.42	0.63	18.47
3	Flexor digitorum brevis	pair	33.10	1.47	16.90
4	Flexor digitorum brevis		33.76	1.62	14.97
5	Extensor digitorum longus		35.93	1.02	18.65

tested are listed in Table 1.

3. Results and Discussions

Figure 1 shows the stress-strain response curves in loading and unloading at the first cycle for the two sets of anatomically paired tendons. The upper pairs are the peroneus longus tendons, while the lower pairs are for flexor digitorum longus tendons. The mechanical reponses of anatomically paired tendons are nearly the same within each pair, however those are different between pairs taken from different anatomical locations. Flexor tendons have much lower peak stresses (about 10 MPa) than peroneus tendons (about 30 MPa).

Figure 2 shows the stress-strain responses of the different (independent) tendons. The peroneus longus tendon is the stiffest and carries the most stress (31.3 MPa) for the peak strain of 3%. The flexor digitorum brevis tendon is the softest and carries the smallest stress (11.5 MPa). This result agrees with the result obtained the flesh human tissue tests (Berg, 1983) but conflicts with the result for the swine digital tendons (Woo et al., 1980 ; Woo et al., 1981 ; Woo, 1986). The cross-sectional areas of the flexor tendons are larger than those of the other (see Table 1). Comparing Figs. 1 and 2, it is clear that anatomically paired

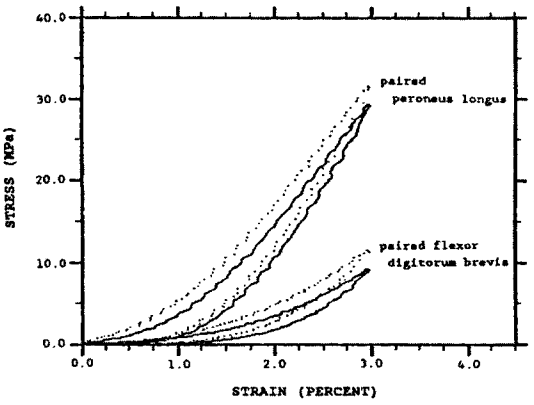

Fig. 1 Stress-strain responses in the two sets of anatomically paried tendon for peroneus longus (test no. 1 and 2) and flexor digitorum brevis (test no. 3 and 4)

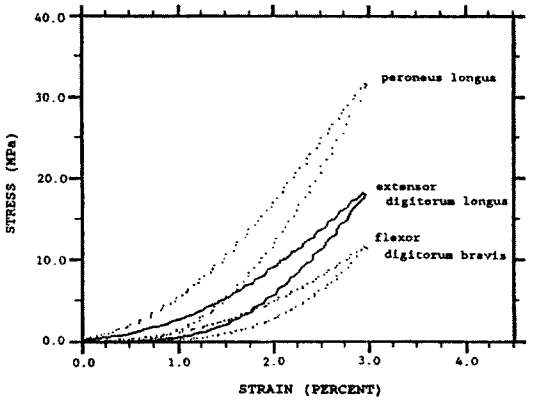

Fig. 2 Stress-strain responses in the different (indepedent) tendons for a peroneus longus (test no. 1), an extensor digitorum longus (test no. 5) and a flexor digitorum brevis (test no. 3)

tendon are similar in mechanical responses than tendons taken from different locations.

The flexor digitorum tendons (test no 3, 4, and 5) carry very small peak loads among all the specimens tested in this study (see Table 1). It is not absolutely certain that our gripping method is free from artifact. The initial lengths of the specimens were intended to be similar, an average value of 32.81 mm ($\pm$1.30 mm, standard deviation), to have similar gripping effect on the each specimen. This intention is believed to make each specimen be free from the length-dependent property of the collagenous soft tissue (Haut, 1988).

4. Conclusion

It was found that the mechanical response of anatomically paired tendons is nearly the same within each pair, however it is different between pairs of tendons taken from different anatomical locations.

Although flexor tendons have much larger cross-sectional area than the others, such as peroneus or extensor tendons, the stiffness and peak stress are much smaller than the others. Mechanical properties of connective tissues, such as tendons and ligaments vary between specimens depending upon anatomical locations. The nature and causes of these differences in the stiffness and stress are not fully known.

However, it is clear that differences in the stiffness and stress of tendons and other connective tissues are significant to the musculoskeletal performance.

The results of this study offer new information about the mechanical responses of collagenous tissues. We knew more about their responses to cyclic extensions and how their responses are different from the anatomical locations. What are the nature of these differences? Future work should answer to this question and concerns, so that we can better understand the tissue response and the musculoskeletal function.

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