Sectional Differences in Tendon Response

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The objectives of this work here focus on the differences in responses to multiple cyclic tests of different sections along the length of the same tendon. Tendon specimens were obtained from the hindlimbs of canines and frozen to −70℃. After thawing, specimens were mounted in the immersion bath at room temperature (22℃), 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 different sections of the same long tendons had different resistances to deformation. In general, the bone end sections were stiffer and carried greater loads for a given strain than the muscle end sections, and the mid-portions were the least stiff and carried the smallest loads for a given strain. The results of this study offer new information about the mechanical responses of collagenous tissues. We know more about their responses to multiple cyclic extensions and how their responses are different from the positions along the length of the tendon specimen. 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 musculoskeletal performance.

Key Words : Tendon, Mechanical Response, Multiple Cyclic Test, Bone End Section, Mid-portion, Muscle End Section, Difference, Musculoskeletal Performance, Connective Tissue

1. Introduction

Tendons are collagenous tissues which connect muscles to bones, and tendons 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.

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There was greater non-linearity for the stress-strain curve for flexor tendon than that for the extensor tendon (Benedict et al., 1968). Flexor tendons inherently had 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 from the different anatomical locations (Berg et al., 1983). They showed that the flexor tendon had lower maximum tensile strength and elastic modulus than the extensor and peroneus tendons. Rhesus knee ligaments varied in modulus, ultimate stress, and rupture stress at different locations in the same joint (Grood et al., 1977). The material properties varied from location to location for human patellar tendons and knee ligaments in the same knee and they varied between different knee ligaments and patellar tendons (Butler et al., 1986). Relaxation response of anatomically paired tendons were generally similar, while that of not-paired tendons was different (Chun and Hubbard, 1986).

During common activities, connective tissues are subjected to numerous cycles of load in diverse and complex situations. Many activities include several thousands mechanical demands on connective tissues. Thus, the response of collagenous tissues to the repeated loading and deformation are central to their bio-mechanical function.

Tendon responses with multiple cyclic extension tests (A, B, C types) were measured. In cyclic tests, there were decreases (relaxations) in the peak stresses. Increasing of the peak stresses (recovery phenomena) occurred predominantly after rest periods (Chun and Hubbard, 2001a).

In all previous works, results have been shown not with sections along the length of the same tendon but with whole tendons.

The objectives of this work here focus on differences in response to multiple cyclic tests of different sections along the length of the same tendon.

2. Materials and Methods

Tendon specimens were obtained from the hindlimbs of canines which had been sacrificed in veterinary surgery classes. Within an hour postmortem, 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 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, then 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) prevented tendon from dehydration and decay during storage. Each specimen was 45 mm or longer with a near constant cross-sectional area. Thick specimens with major diameters larger than 3 mm and minor diameters smaller than 1 mm were avoided, since 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, servo-hydraulic Instron testing system (Model, 1331) with its hydraulic cylinder in the upper crosshead. For gripping 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 extensions. The marks were not detected by the microscope shown by photographs, indicating that no detectable slippage occurred with 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 they were neither torn nor fractured.

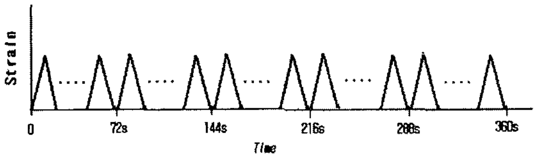
Grip motion was measured with an LVDT mounted in the hydraulic actuator of the Instron testing machine. The load was measured with a fully submersible Interface load cell (Model SSM-A5-100) which has a maximum 444.82 N load and was mounted in the immersion bath. The initial length of the specimen was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

As in 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 is accurate to within 0.01 mm^2.

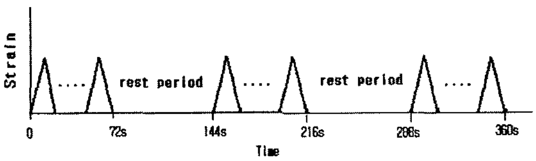
A PDP-11/23 computer was used for test control and data acquisition, storage, and analysis. An Instron Machine Interface Unit and an Instron Machine Driver enable command and communication between the computer and the testing machine.

Data were also monitored and stored on a Nicolet digital oscillosope (Model 201, series 2090).

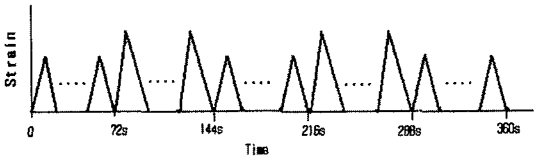
The multiple cyclic tests were selected (Chun and Hubbard, 2001a). They involved three different type of cyclic test sequences (see Figure 1). The tests were performed with five sections of cycles each lasting 72 sec for a total test time of 360 sec. One sequence (A-type) was continuous cyclic extensions with peak strain level of 3% for all five sections of the test. Another sequence (B-type) was the same as the first one but with



(a) Constant peak strain level test (A-type)



(b) Constant peak strain level test with rest periods (B-type)



(c) Different peak strain level test (C-type)

Fig. 1 Illustrations of the multiple cyclic test sequences (A, B, C-type tests)

two rest periods during the second and fourth

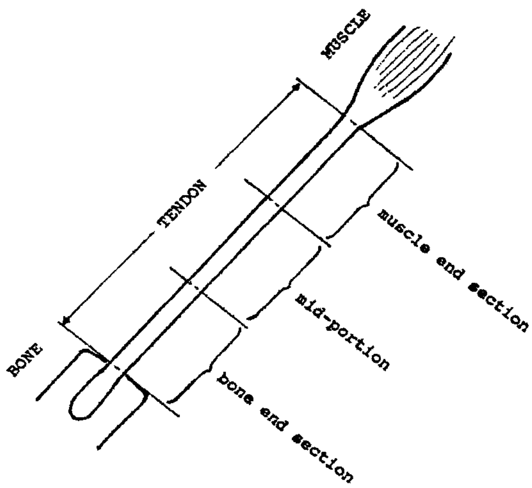


Fig. 2 Illustration of the same tendon which is divided into three sections (bone end section, mid-portion, muscle end section)

Table 1 Tendon Specimen Characteristics

Test No	Anatomical Location	Section Status	Initial Length (mm)	Area (mm^2)	Peak Load (N)
1	Peroneus digitorum longus	b.e.s.	32.42	0.63	18.47
2	Peroneus digitorum longus	m.p.	32.61	0.61	12.50
3	Peroneus digitorum longus	m.e.s.	31.47	0.68	16.05
4	Flexor digitorum longus	b.e.s	31.28	1.34	17.65
5	Flexor digitorum longus	m.p.	32.29	1.05	3.66
6	Flexor digitorum longus	b.e.s.	31.89	1.63	7.21
7	Flexor digitorum longus	m.p.	33.67	1.10	2.11

b.e.s. : bone end section, m.p. : mid-portion, m.e.s. : muscle end section sections of the test. The third sequence (C-type) was the cyclic extensions with 3% peak strain during the first, third, and fifth section of the test alternation with 4% peak strain during the second and fourth sections. Peak strain levels of 3% and 4% were chosen to study strain level and sequence sensitivity. The 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 as an intermediate between rapid and slow physiological movement.

Figure 2 shows the description of specimens from the same tendon which is divided into three sections (bone end section, mid-portion, muscle end section).

The test number, anatomical location, section status, cross-sectional area, initial length, and peak load (N) for each tendon specimen tested are listed in Table 1.

3. Results and Discussions

Figure 3 shows load responses from separate tests of three sections of the same tendon with cycles at 3% peak strain level. In this figure, the

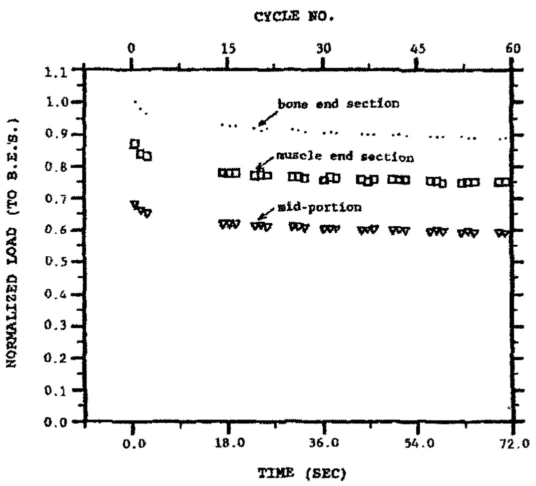


Fig. 3 Normalized load responses to the first peak load of the bone end section for the bone end section (test no. 1), mid-portion (test no. 2), and muscle end section (test no. 3) form a tendon of peroneous longus with the first sixty cycles

peak loads in each section from the same tendon are shown as normalized so that the peak of the frist cycle of the bone end section has a value of 1.0. The peak normalized loads rapidly decreased for the first few cycle of testing, then continued to decrease to a lesser degree. For the 3% peak strain level, the bone end section carried about 13% more loads than the muscle end section and about 32% more loads than the mid-portion throughout 60 cycles. Figure 4 shows these phenomena in stress-strain plots with loading and unloading curves at the first cycle for each section. The bone end section was stiffer and carried greater stress (29.3 MPa) for the peak strain of 3% than the other sections, and the mid-portion was the softest and carried the smallest stress (20.5 MPa).

Figure 5 shows a normalized (to the bone end section at the first peak) load response for a tendon of flexor digitorum longus with two rest periods (the B-type test). Here, the specimen from the muscle end section was not available by a mistake during dissecting. The load responses of the mid-portion were about 78% less than those of the bone end section throughout the entire 180 cycles. The amounts of load recovery after the first rest periods were 2.4% for both the bone end section and the mid-portion. After the second rest periods, the recovery was 2.1% for the bone end section and 2.4% for the mid-

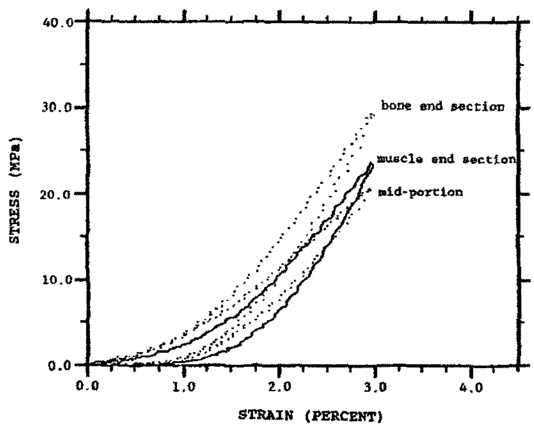


Fig. 4 Stress-Strain responses for the bone end section (test no. 1), mid-portion (test no. 2), and muscle end section (test no. 3) form a tendon of peroneus longus at the first cycle

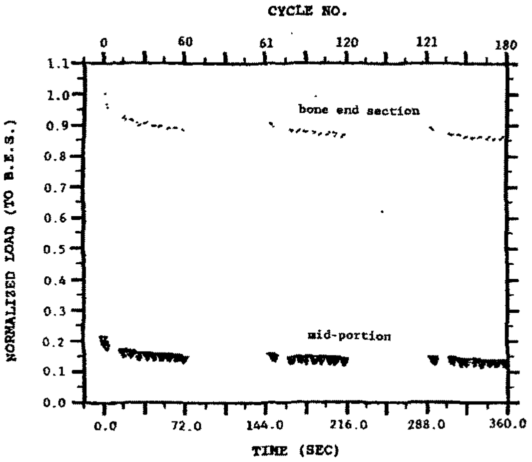


Fig. 5 Normalized load responses to the first peak load of the bone end section for the bone end section (test no. 4) and mid-portion (test no. 5) from a tendon of flexor digitorum longus with two rest periods at the B-type test

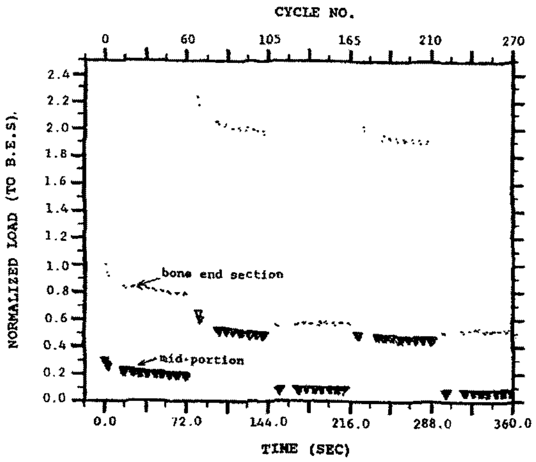


Fig. 7 Normalized load responses to the first peak load of the bone end section for the bone end section (test no. 6) and mid-portion (test no. 7) from a tendon of flexor digitorum longus at the C-type test

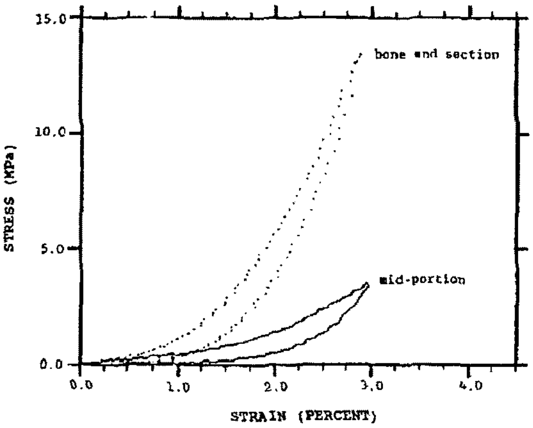


Fig. 6 Stress-Strain responses for the bone end section (test no. 4) and mid-portion (test no. 5) from a tendon of flexor digitorum longus at the first cycle

portion. Figure 6 shows stress-strain plots with loading and unloading curves at the first cycle. The bone end section was much stiffer and carried greater peak stress (13.4 MPa) than the mid-portion (3.5 MPa).

Figure 7 shows load response normalized to the first peak for the bone end section and mid-portion specimens of flexor digitorum longus tendon in the C-type tests. Here, the specimen from the muscle end section was not available by a mistake during dissecting. For the first few cycles, peak loads in both specimens rapidly decreased then continued to decrease to a lesser degree in the first cyclic block (from the first to the 60th cycle, 3% peak strain level).

In the second cyclic block (from the 6lst to the 105th cycle) where the peak strain level was 4%, the peak loads were much greater than the peak loads of the first cyclic block. This increase in stress from 3% to 4% strain was consistent with the nonlinear stress-strain response for tendon. In this cyclic block, the peak loads decreased as in the first cyclic block.

In the third cyclic block (from the 106th to the 165th cycle, 3% peak strain level), the peak loads did not relax, but rather they increased (recovered) a little with successive cycles. In the fourth cyclic block (from the 166th to the 210th cycle, 4% peak strain level), the responses were like those of the second cyclic block. Also, in the fifth cyclic block (from the 211th to the 270th cycle, 3% peak strain level), the responses were similar to those of the third cyclic block. The peak loads recovered (increased) 0.9% in the third cyclic block and 2.8% in the fifth cyclic block for the bone end section, and those recovered 3.1% in the third and fifth cyclic blocks for the mid-portion.

During the first block of cycles with peak strains of 3% and the second and fourth blocks of cycles to 4% peak strain, the peak stresses were about four times smaller in the mid-portion than in the bone end section. During the third and fifth blocks of extension to 3% peak strain after the 4% extensions, the stresses in the mid-portion were smaller by an even greater factor of about six. Thus, the effects of 4% peak strains were to lower the subsequent stresses in the mid-portion to a greater degree than in the bone end section.

4. Conclusion

It was found that different sections of the same long tendons had different resistances to deformation. In general, the bone end sections were stiffer and carried greater load for a given strain than the muscle end sections, and the mid-portions were the least stiff and carried the smallest loads for a given strain.

Mechanical properties of connective tissues, such as tendons and ligaments, vary between specimens depending upon anatomical locations (Chun and Hubbard, 2003) and within a specimen depending upon the positions. 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 musculoskeletal performance.

The results of this study offer new information about the mechanical responses of collagenous tissues. We know more about their responses to multiple cyclic extensions and how their responses are different from the positions along the length of the tendon specimen. What are the nature of these differences ? Future work should address this question and concerns so that we can better understand tissue responses and musculoskeletal function.

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