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Constitutive Model of Tendon Responses to Multiple Cyclic Demands (I)

— Experimental Analysis —

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The work reported here is an extensive study of tendon response to multiple cyclic tests including 3% constant peak strain level test (A-type test), 3% constant peak strain level test with two rest periods (B-type test), and 3~4% different peak strain level test (C-type test). A sufficient number of specimens were tested at each type of the test to statistically evaluate many changes in response during testing and differences in response between each type of the test. In cyclic tests, there were decreses (relaxations) in the peak stresses and hysteresis, increases in the slack strains, and during lower peak strain level (3%) cyclic block after higher peak strain level (4%) cyclic block in the C-type tests. Considering the results of this study and those of the other study of multiple cyclic tests with rest periods by Hubbard and Chun, 1985, recovery phenomena during the rest periods occurred predominantly at the beginning of the rest periods. Consistently in both studies, the effects of rest periods were small and transient compared to the effects of the cyclic extensions. The recovery with cycles at lower peak strain level (3%) after higher peak strain level (4%) in the C-type test has not been previously documented. This recovery seems to be a natural phenomena in tissue behavior so that collagenous structures recover during periods of decreased demand.

Key Words : Relaxation, Recovery, Stress, Hysteresis, Slack Strain, A-type, B-type, C-type

1. Introduction

Tendon is a collagenous tissue which connects muscle to bone and remains rather inextensible relative to muscle during contraction. The tendon consists primarily of collagen fibers with a small percentage of elastin fibers and a matrix of the ground substance. In the study of mammalian tendons, Elliot, 1965 shows that collagen fibers constitute 70~85% of the dry weight of the tendon while the content of elastin fibers make up only 2% of the dry weight. The main function of tendon is to transmit force between muscle and bone.

In the study of mechanical properties of tendon, the response of collagen fibers is predominant in comparison with response of the elastin fibers and matrix of ground substance. However, the elastin fibers and ground substance may contribute in crimping the tissue when the load is released. The matrix of ground substance surrounds the fibers in the tendon and aids in metabolism by passively transporting nutrients and waste. The ground substance is a gel and its mechanical role is not clear yet. Yannas, 1972 ignores the mechanical role of this material. Partington and Wood, 1963 conclude that the ground substance has significantly less mechanical effect than the elastin fibers. The ground substance may play a key role in the physiological conditions which are impor-

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tant to tissue behavior.

During the course of common activities, people subject their connective tissues to numerous cycles of load in diverse and complex situations. Many human activities include several thousand mechanical demands on connective tissue. Thus, the response of collagenous tissue to the repeated loading and deformation are central to their biomechanical function. Experimental data for cyclic extension are limited (Haut and Little, 1972; Hubbard and Chun, 1985; Sacks, 1983; Woo, et al, 1981).

The objective of this work are to continue measurement and analysis the changes in the responses of connective tissues to repeated cyclic extension, effects of rest periods, and effects of a specific strain level of cyclic extensions by the previous extensions at a different strain level. This experimental work has been part of research to develop a constitutive model for tendons which are subjected to multiple cyclic extensions. This constitutive modeling is presented in a companion paper (Chun and Hubbard, 1987b).

2. Materials and Methods

Tendon specimens were obtained from the hindlimbs of seven canies which had been sacrificed in veterinary surgery classes. Within a hour postmortem the whole limbs were refrigerated at near freezing, and tendons dissected within two days, 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. Groups of tendons from each canine were put into a larger plastic bag, and these larger plastic bags were put into a air-tight container and stored in a freezer at −70℃. Each specimen was 45mm or longer with a near constant cross-sectional area. Thick specimens with major diameters larger than 3mm and minor diameters greater than 1mm were avoided, since it was thought that large cross-sections would not insure the uniform pressure between interior and exterior fibers during gripping. This storage method (Hubbard and Chun, 1985; Sacks, 1983) prevented tendon dehydration and decay during storage.

At the beginning of each test, a tendon specimen was soaked in the Ringer's lactate solution for a minimum of 30minutes during which there was complete thawing. Tests were conducted with a computer controlled, servo-hydraulic Instron testing system (Model 1331). For gripping tendon samples, flat-plate clamp type grips were employed with waterproof 100 grit silicon carbide abrasive papers in the inner surface. All specimens were marked with a water resistant pen so that these marks were placed just inside of the grips. These marks were observed and photographed with a WILD MPS 55 stereo-microscope and its camera during the tests. No marks were detected by the microscope and shown by photographs. This result indicated no slippage occurred with this gripping method.

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 100lb load. Initial specimen length was measured between grips by a micrometer with an accuracy of 0.01mm at a preload of 0.13N. During the testing, specimen was immersed in a Ringer's lactate solution bath at a room temperature (22℃).

As were used in previous studies (Hubbard and Chun, 1985; Sacks, 1983), the cross-sectional areas of the samples were measured from historical cross-sections prepared with commonly used paraffin embedding (Thompson, 1966). 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 bundles cross-section was selected and measured using a Numonics digitizer which was accurate to within 0.01mm^2. The test number, anatomical site, area, initial length, and peak load (N) for each specimen tested are listed in Table 1.

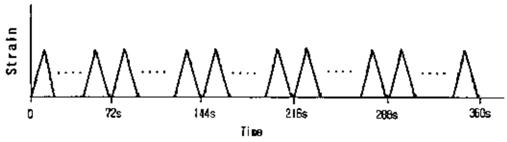
A PDP-11/23 computer was used for test control and data acquisition, storage, and analysis. An Instron Machine Interface Unit and an Instron Machine Driver enabled command and communication between the computer and testing machine. Data were also monitored and stored on

Table 1 Tendon specimen characteristics in multiple cycle tests

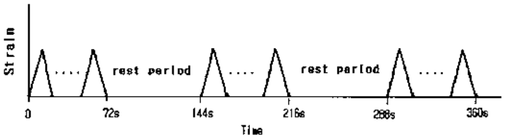
Test Type-No.	Anatomical Location	Inintial Length (mm)	Area (mm^2)	Peak Load (N)
A-1	Peroneous longus	32.54	0.58	18.23
A-2	Peroneous longus	32.42	0.63	18.47
A-3	Flexor digitorum brevis	33.10	1.47	16.90
A-4	Flexor digitorum brevis	33.76	1.62	14.97
A-5	Extensor digitorum brevis	35.93	1.02	18.65
A-6	Extensor digitorum brevis	33.04	1.33	14.25
B-1	Peroneous longus	32.61	0.61	12.50
B-2	Peroneous longus	31.47	0.68	16.05
B-3	Extensor digitorum longus	33.70	1.07	15.23
B-4	Extensor digitorum longus	32.56	0.92	17.38
B-5	Flexor digitorum longus	32.29	1.05	3.66
B-6	Flexor digitorum longus	31.28	1.34	17.95
C-1	Peroneous longus	34.28	0.90	10.02
C-2	Extensor digitorum longus	33.35	0.55	7.17
C-3	Peroneous longus	30.68	1.00	11.94
C-4	Peroneous longus	34.21	1.21	12.09
C-5	Flexsor digitorum longus	33.67	1.10	2.11
C-6	Flexsor digitorum longus	31.89	1.63	7.21

a Nicolet digital oscilloscope (Model 201, Series 2090).

The multiple cyclic tests involved three different type of cyclic test sequences (See Fig. 1) all including extension cycles from zero to some peak strain levels. The tests were performed with five sections of cycles each lasting 72sec for a total test time of 360sec. 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 two rest periods during the seconds and fourth sections of the test. The third sequence (C-type) was the cyclic extensions with 3% peak strain during the first, third, and fifth sections of the test alternating with 4% peak strain during the second and fourth sections. Maximum strain level of 3% and 4% were chosen to study strain level 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%/



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



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

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

Fig. 1 Illustrations of the multiple cyclic test sequences sec was chosen as an intermediate between rapid and slow physiological movement (Hubbard and Chun, 1985; Sacks, 1983).

Six tendon specimens were tested with each sequence.

3. Results and Discussion

3.1 Cyclic relaxation and recovery

A typical load-time response of a tendon in an A-type cyclic extension test is shown in Fig. 2. The peak loads of cycles are shown as normalized so that the peak of the first cycle has a value of 1.0. This normalization facilitates comparison and summary of result from different specimens. The peak normalized loads rapidly decreased for the first few cycles of testing then continued to decrease to a lesser degree. Figure 3 shows the corresponding stress-strain plots with loading and unloading curves at the first, 60th (72sec), and 300th (360sec) cycles. In this figure, the initial extension (upper curve at the first cycle) starts at zero strain (no slack strain) and proceeds with an increasing slope of the loading curve. Also, the slack strain of this unloading curve is about 0.6%. In the 60th cycle, the specimen must be extended to a strain of about 0.8% before it bears load (loading slack strain) and the unloading slack strain is 0.9%. In the 300th cycle, the loading slack strain is about 0.9% and the unloading slack strain is over 1.0%.

Table 2 shows the statistical summary of normalized cyclic load relaxation for A-type tests. The average peak normalized load decreased by 14.1% in 60 extension cycles and by 20.5% for the entire test of 300 cycles.

Table 2 Summary of normalized cyclic load relaxation (%) with 95% confidence interval for A-type tests

Cycle No. Time	1	2	3	60 72sec	120 144sec	180 216sec	240 288sec	300 360sec
A-1	100.0	96.3	95.5	85.8	81.6	79.6	77.4	76.3
A-2	100.0	97.9	96.5	88.6	86.0	84.4	82.3	81.0
A-3	100.0	97.4	95.4	85.7	84.3	84.0	82.1	80.9
A-4	100.0	96.5	94.5	85.4	82.4	81.8	81.1	80.2
A-5	100.0	96.5	95.1	86.7	84.7	83.3	82.0	80.3
A-6	100.0	95.3	94.1	83.3	80.9	78.6	78.3	78.0
Ave.	100.0	96.7	95.2	85.9	83.3	82.0	80.5	79.5
S.D	0.0	0.9	0.8	1.7	2.0	2.4	2.1	1.9
95%C.I	0.0	0.9	0.8	1.8	2.1	2.5	2.2	2.0

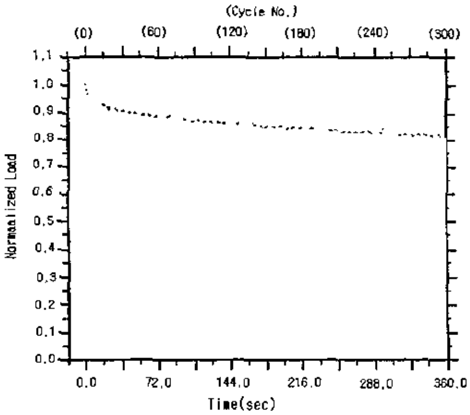


Fig. 2 Normalized cyclic load relaxation for an A-type test

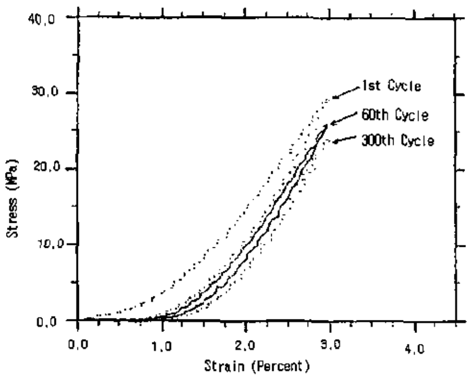


Fig. 3 Stress-Strain responses with cycles for an A-type test

The typical normalized peak load-time response of a tendon in a B-type cyclic extension test is shown in Fig. 4. The relaxation in the first cyclic block (0 to 72 sec) is similar to an A-type test. At the beginning of cyclic testing periods after the two rest periods (at 144sec, 61st cycle and at 288sec, 121st cycle), the peak loads recovered (increased) from the peak load values just before the rest periods, then they relaxed quickly in a few cycles and continued to relax throughout the cyclic test periods.

Table 3 shows the statistical summary of normalized cyclic load relaxation for the B-type tests. Individual recovery, defined as the percent difference between the last peak load before the rest period and the first peak load after the rest period, is shown to be nonzero. Load recovery after the first rest period was generally greater than after the second rest period. The average value of recovery with a 72 sec rest period is 2.9% after the first rest period and 2.5% after the second rest period. Hubbard and Chun, 1985 showed that the average value of recovery with an 1800sec rest period was 3.9% after the first rest period and 3.3% after the second rest period at a 3% peak strain level. These results show that there is more recovery of peak load with a longer rest period, but most of the recovery occurs in the beginning of the rest period. The values of peak normalized load of each cycle in the B-type test were not statistically different from those of corresponding cycles in the A-type test via a t-test at p=0.05.

The typical load time response of a tendon in a C-type cyclic extension test is shown in Fig. 5.

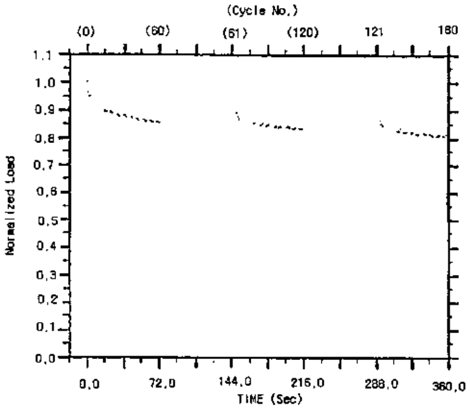


Fig. 4 Normalized cyclic load relaxation for a B-type test

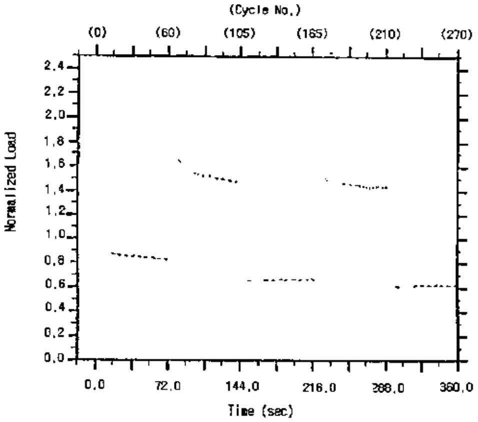


Fig. 5 Normalized cyclic load relaxation for an C-type test

Table 3 Summary of normalized cyclic load relaxation (%) with 95% confidence interval for B-type tests

Cycle No. Time	1	2	3	60 72sec	61 144sec	120 216sec	121 288sec	180 360sec
B-1	100.0	97.6	96.2	86.9	89.2	83.8	86.8	81.7
B-2	100.0	96.5	95.4	85.1	87.4	83.6	85.5	81.2
B-3	100.0	96.3	95.4	85.1	89.3	84.5	86.7	82.8
B-4	100.0	96.2	94.9	85.3	89.1	83.3	86.5	81.5
B-5	100.0	93.5	87.5	69.0	71.4	63.7	66.1	60.7
B-6	100.0	96.8	95.6	87.9	90.3	86.5	88.6	85.8
Ave.	100.0	96.2	94.2	83.2	86.1	80.9	83.4	79.0
S.D	0.0	1.4	3.3	7.1	7.3	8.5	8.5	9.1
95%C.I	0.0	1.5	3.5	7.5	7.7	8.9	8.9	9.6

Table 4 Summary of normalized cyclic load relaxation (%) with 95% confidence interval for C-type tests

Cyc No	1	2	3	60	61	105	106	165	166	210	211	270
Time(s)						144s		216s		288s		360s
PKSL	3	3	3	3	4	4	3	3	4	4	3	3
C-1	100.0	96.2	93.5	82.0	164.4	147.8	65.2	66.3	150.2	143.3	60.9	62.6
C-2	100.0	95.1	92.7	77.2	190.3	164.8	54.7	56.5	169.6	156.8	49.8	50.8
C-3	100.0	95.4	93.4	81.6	166.6	146.4	61.7	64.2	151.5	143.1	57.7	58.9
C-4	100.0	96.4	94.6	83.8	172.1	155.7	65.6	68.1	158.2	151.2	61.6	63.4
C-5	100.0	89.7	84.5	60.8	217.6	162.9	25.7	28.8	165.0	152.6	19.5	22.6
C-6	100.0	94.0	91.5	78.2	223.3	195.8	55.9	56.8	201.2	191.6	50.4	53.2
Ave.	100.0	94.5	91.7	77.3	189.1	162.2	54.8	56.8	166.0	156.4	50.0	51.9
S.D	0.0	2.5	3.7	8.4	26.0	18.1	15.0	14.5	18.8	18.1	15.8	15.2
95% CI	0.0	2.6	3.9	8.8	27.3	19.0	15.7	15.2	19.7	19.0	16.6	16.0

Cyc No. : Cycle Number
PKSL : Peak Strain Level (%)
95% CI : 95% Confidence Interval

The peak loads from cycles are normalized load relaxation at the first cyclic block (0 to 72sec) was similar to that of A and B-type tests. In the second cyclic block (72 to 144sec), the peak strain level is 4% and the loads were much greater than loads of the first cyclic block (3% peak strain level). The peak normalized loads rapidly decreased for the first few cycles then continued to decrease to a lesser degree as in the first cyclic block. In the third cyclic block (144 to 216sec), the peak loads did not relax, but rather they increased (recovered) a little with successive cycles. In the fourth cyclic block (216 to 288sec, 4% peak strain level), the responses were like those of the second cyclic block.

The recovery with initial cycles at the lower peak strain level (3%) after the higher peak strain level (4%) seems to be natural phenomena in tissue behavior. Tendons recover during periods of lower extensions after higher extensions.

Table 4 presents the statistical summary of cyclic load relaxation in the C-type tests. The average values of relaxation in normalized load are 26.9% in the second cyclic block and 10.4% in the fourth cyclic block. The average values of recovery are 2.0% in the third cyclic block and 1.9% in the fifth cyclic block. The values of peak normalized load from the first to 60 th cycle were not statistically different from those their corresponding cycles in the A and B type tests via a t-test at p=0.05.

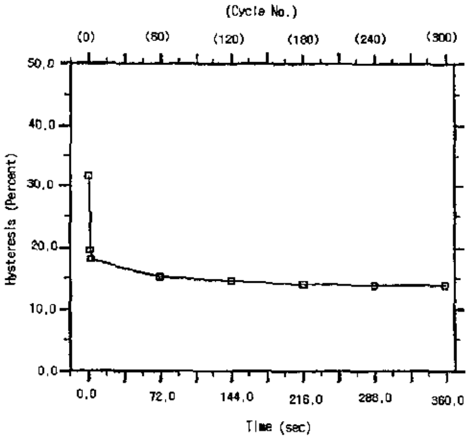


Fig. 6 Average hysteresis (%) in the A-type tests

3.2 Hysteresis

The hysteresis is defined by the following equation:

$$Hysteresis\,(\%) = \frac{Energy\ loading - Energy\ unloading}{Energy\ loading} \times 100$$

Figure 6 shows the average hysteresis versus time in the A-Type tests. Hysteresis rapidly decreased for the first few cycles of testing then continued to decrease to a lesser degree as in the

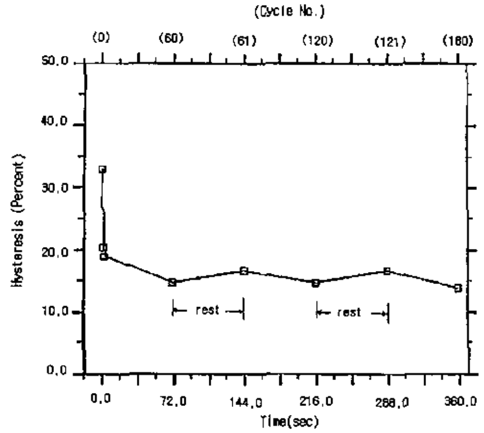


Fig. 7 Average hysteresis (%) in the B-type tests

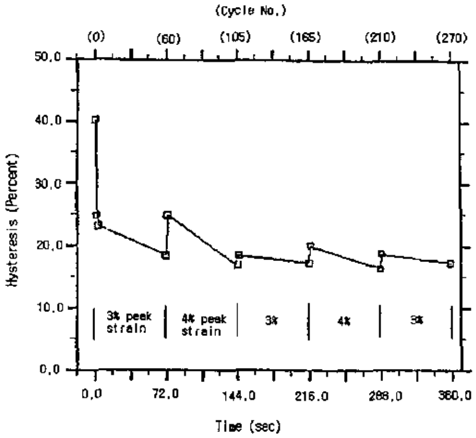


Fig. 8 Average hysteresis (%) in the C-type tests

case of the normalized cyclic peak load. The average values of hysteresis decreased during 300 cycles from an initial value of 31.7% (±5.0, 95% Confidence Interval) to a final value of 13.7% (±1.7, 95% C.I.).

Figure 7 shows the average hysteresis versus time in the B-type tests. Hysteresis for each cycle decreases within each cyclic block, and some recovery occurred after each rest period as in the case of the normalized cyclic peak load. The average values of recovery in hysteresis with a 72sec rest period were 2.0% for the first rest period and 1.9% for the second rest period. Hubbard and Chun, 1985 showed that the average values of recovery with an 1800 sec rest period were 2.8% for the first rest period and 2.0% for the second rest period at a 3% peak strain level. These results show that there was more recovery with longer rest period as in the case of the normalized cyclic peak load. Hysteresis values of each cycle in the B-type tests were not statistically different from those of their corresponding cycles in the A-type test via a t-test at p=0.05.

Figure 8 shows the average hysteresis versus time in the C-type tests. Hysteresis within each cyclic block decreases as in the A and B-type tests. However, there are increases after transitions to both 3% and 4% peak strain levels. Hysteresis values of each cycle in the C-type tests were not statistically different from those of their corresponding cycles in the A-type test via a t-test at p=0.05.

The decreases of hysteresis between the first and second cycles were more than half of the overall decreases. For all the test type, the range of the average hysteresis value is 32% to 40% for the first cycle, 20% to 25% for the second cycle and 14% to 17% for the last cycle. The hsysterises values for the cycle in the present study are comparable to canine (Hubbard and Chun, 1985) values of 34% to 37%.

The values (14% to 17%) of hystsersis at 360 sec in the present study are comparable to other studies of canine tendons: 16% to 20% hystersis (Hubbard and Chun, 1985) at 9000 sec with two rest periods (each 1800 sec) and 17% to 22% hysteresis (Sacks, 1983) at 9000 sec with no rest period.

3.3 Slack strain

As the distance between the grips increases in a test, loading slack strain is the smallest strain for which tensile stress is applied in the tendon specimen. As the distance between the grips decreases in a test, unloading slack strain is the largest strain for which tensile stress is no longer applied in the tendon specimen.

Figure 9 shows the average values of loading and unloading slack strains in the A-type tests. The slack strains rapidly increased in the first few cycles of testing then continued to increase to a lesser degree. The range of average values for loading slack strains was from an initial value of 0.0% to final value of 1.08% (±0.19, 95% Confi-

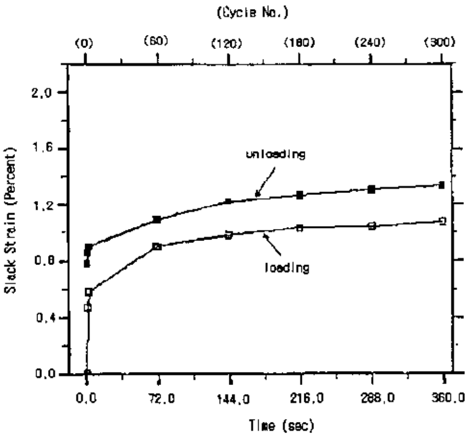


Fig. 9 Average loading and unloading slack strain (%) in the A-type tests

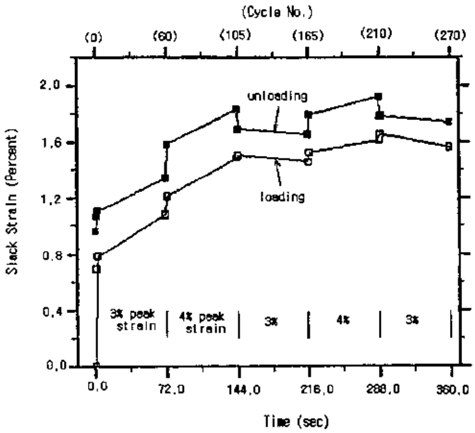


Fig. 11 Average loading and unloading slack strain (%) in the C-type tests

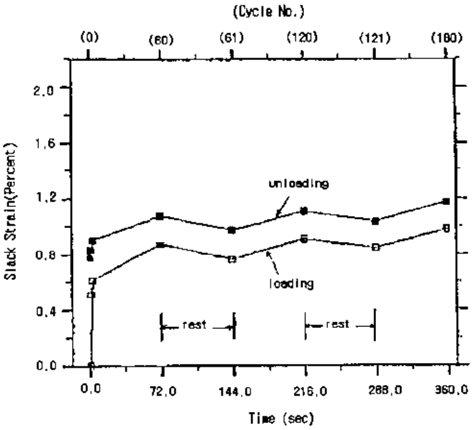


Fig. 10 Average loading and unloading slack strain (%) in the B-type tests

dence Interval). For unloading slack strains, this range was from 0.80% (±0.20, 95%, C.I.). to 1.32% (±0.22, 95%, C.I.).

Figure 10 shows the average values of loading and unloading slack strains in the B-type tests. Slack strain increased within each cyclic block, and recovery (decreasing of the slack strain) occurred after each rest period. Individual recovery for each test was nonzero in each rest period. The average values of recovery in the 72sec rest periods for both loading and unloading slack strains were 0.09% for the first rest period and 0.11% for the second rest period. Hubbard and Chun, 1985 found that the average values of recovery in loading slack strain during 1800sec rest periods were 0.20% for the first rest period and 0.17% for the second rest period. Thus, there is more recovery with a longer rest period. Slack strain in each cycle for loading and unloading for B-type tests were not statistically different from those in corresponding cycles in the A-type tests via a t-test at p=0.05.

Figure 11 shows the average values of loading and unloading slack strains in the C-type tests. Slack strains rapidly increased for the first few cycles of testing then continued to increase to a lesser degree. There is an abrupt increase at change from 3% to 4% peak strain. Slack strains recovered (decreased) with return to 3% peak strain in the third cyclic block (from 144 to 216sec) and fifth cyclic block (from 288 to 360sec) as in the cases of the normalized cyclic load and hysteresis. The unloading slack strain decreased at 144 and 288sec while the loading slack strains increase at these times in the C-type test. Slack strains from the 1st to 60th cycle were not statistically different from those in corresponding cycles in the A and B-type tests via a t-test at p=0.05.

At the beginning of the test, the initial length of the tendon specimen was adjusted so that a tendon specimen was slightly extended and bearing a small load of 0.13N. Thus, there was no slack strain at the first loading. The effect of each rest period was to reduce the slack strain, which then increased during the following cycles. The

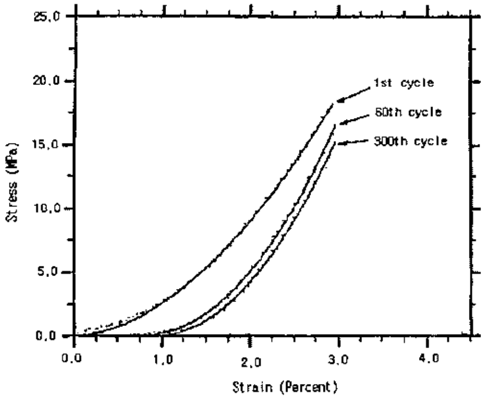


Fig. 12 Typical stress-strain responses for the 1st, 60th, 300th Cycle at a 3% peak strain level with regression fits (……: experimental data, ——: fitted line)

changes in slack strain accompany the changes in peak load and hysteresis. The average value of the first unloading slack strain is 0.85% for all eighteen specimens. This average value of unloading slack strain from the first cycle will be used as input to the constitutive model for comparison of predicted results with measured data.

3.4 Power fits to stress-strain response

As in the previous works (Hubbard and Chun, 1985; Sacks, 1983), stress-strain responses were fit with a linear regression equation of the form:

$$Log\,(stress) = Log\,(C) + d\,[Log\,(\varepsilon - \varepsilon_s)]$$

This fitting resulted in high correlation coefficients of 0.99 or greater.

Taking the antilog of this relation yields:

$$\sigma = C(\varepsilon - \varepsilon_s)^d$$

where ε is the strain, ε_s is the slack strain, d is the power coefficient, and C is the scale factor from the measured data.

Figure 12 shows typical stress-strain data from a test with a maximum strain of 3% and the regression curve superimposed over it for the first ($d=1.83$, $C=11.51$GPa, $\varepsilon_s=0.0\%$), 60th ($d=2.08$, $C=42.75$ GPa, $\varepsilon_s=0.8\%$), and 300th ($d=1.97$, $C=31.83$ GPa, $\varepsilon_s=1.0\%$) cycle.

The range of values of d for the first cycle of loading was from 1.67 to 2.48. For the first cycle of unloading the range in values of d was from 1.60 to 3.12. The average value of d for the first cycle of loading is 2.05 and unloading is 2.30 for all eighteen specimens, but these values are not statistically different at $p=0.05$ level. Hubbard and Chun, 1985 found that the values of d for loading were from 1.41 to 2.45, with most values around 2.0. Haut and Little, 1972 also selected the value of 2.0 for this power coefficient for collagenous tissues.

The coefficient C acts as a scale factor in the regression similar to a modulus in a linear stress-strain relationship. The range of values of C for the first cycle of loading was from 0.86 to 64.01GPa and for unloading was from 9.73 to 353.23 GPa. Large scatter for C is shown both from cycle to cycle within a specimen and between specimens. The cycle to cycle scatter indicates changes in response during the tests with only significant difference being the increase between the first and second cycles. This difference is probably related to differences in tissue fiber composition and geometry.

For rat tail tendons, Haut and Little, 1972 reported that C varied between 18.0 and 31.4 GPa, but the average value of C was 23.06 GPa with a standard deviation of 3.75 GPa at various strain rates. Recently, Hubbard and Chun, 1985 found, for canine tendons like those in the present study, that the average value of C for the first cycle of loading was about 17.0 GPa with large standard deviation of 16.6 GPa.

4. Conclusions

The work here is an extensive study of tendon responses to multiple cyclic tests including 3% constant peak strain level test (A-type test), 3% constant peak strain level test with two rest periods (B-type test), and 3%-4% different peak strain level test (C-type test). A sufficient number of specimens were tested at each type of the test to statistically evaluate many changes in response during testing and differences in response between each type of the test.

In cyclic tests, there were decreases (relaxations) in the peak stresses and hysteresis, increases in the slack strains, and reversals (recoveries) of these changes during rest periods in the B-type tests and during lower peak strain level (3%) cyclic block after higher peak strain level (4%) cyclic block in the C-type tests. Considering the rest with rest periods by Hubbard and Chun, 1985, recovery phenomena during the rest periods occurred predominantly at the beginning of the rest periods. Consistently in both studies, the effects of rest periods were small and transient compared to the effects of the cyclic extensions. The recovery with cycles at lower peak strain level (3%) after higher peak strain level (4%) in the C-type test has not been previously documented. This recovery seems to be a natural phenomena in tissue behavior so that collagenous structures recover during periods of decreased demand.

The tests in this study were conducted in vitro with no attempt to maintain cell viability. The effects of active biological mechanisms in the relaxation and recovery of connective tissues could effect these responses but they await future study. It is not absolutely certain that our gripping method was free from artifact. As in previous works (Hubbard and Chun, 1985; Sacks, 1983), our methods for gripping the tendons resulted in compressed but not ruptured tendon fibers as seen in histological examination of the gripped regions. No slippage was apparent by examination of tendon at the grip edge with a microscope during testing.

This study has shown that tendons relax and become less resistant to deformation with repeated extensions as seen in increases in slack strains and decreases in peak stresses. Also, during periods of rest or reduced strain, the tissues recover some of their previous resistance to extension as indicated by decreases in slack strain and increase in peak stress. The relaxation and recovery of connective tissue resistance are significant to musculoskeletal performance. Decreases in resistance of tissues to deformation are evident as tissues are repeatedly stretched in activities of daily living, athletic performance, and manipulative therapy. Such changes in tissue resistance are commonly transient and reversible during inactive periods.

The results of this study offer new information about the mechanical nature of collagenous tissue. We know more about their responses to multiple cyclic tests and how their responses relax and recover revert during rest periods or during lower peak strain level after higher peak strain level. Recovery phenomena in tendon responses indicate that decreases in resistance to extension are at least partially reversible. The extent and nature of this reversion was not fully evaluated in this study and remains for a future work.

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