

Tensile and Viscoelastic Properties of Human Patellar Tendon

Greg A. Johnson, Dawn M. Tramaglino, Rebecca E. Levine, Kazunori Ohno,
 Nam-Yong Choi, and Savio L-Y. Woo

*Musculoskeletal Research Center, Department of Orthopaedic Surgery,
 University of Pittsburgh, Pittsburgh, Pennsylvania, U.S.A.*

Summary: The tensile and viscoelastic properties of fresh-frozen, nonirradiated human patellar tendon were investigated in two groups of 15 specimens: one group was from individuals 29-50 years old and the other group was from individuals 64-93 years old. The central portion of each patella-patellar tendon-tibia complex was subjected to cyclic preconditioning, stress-relaxation, cyclic stress-relaxation, and load to failure tests. For each age group, stress-relaxation and stress-strain curves were obtained, from which percentage relaxation, ultimate tensile strength, strain at failure, modulus, and strain energy density were determined. Viscoelastic behavior was described with use of quasilinear viscoelasticity. The younger group showed a $46 \pm 9\%$ (mean $\pm$ SD) decrease in stress after 15 minutes, whereas the older group exhibited a $50 \pm 6\%$ decrease. The values for ultimate tensile strength and strain at failure, respectively, were 64.7 ± 15.0 MPa and $14 \pm 6\%$ for the younger group and 53.6 ± 10.0 MPa and $15 \pm 5\%$ for the older group. Modulus values were 660 ± 266 MPa for the younger group and 504 ± 222 MPa for the older group. Except for ultimate tensile strength, which was 17% less for the older group than for the younger one, no statistically significant differences were found in tensile or viscoelastic properties. This study indicated that there were minimal differences in biomechanical properties of the substance of the patellar tendon between younger and older age groups.

Surgical treatment of a ruptured anterior cruciate ligament often involves replacement of the damaged ligament with a graft, especially for young and active patients. Although many different materials have been used (7), patellar tendon is the most frequent choice because of its high tensile stiffness and strength and because it can be harvested with bone blocks on both ends (3,4,7,14). Allograft patellar tendon typically is taken from donors 55 years of age or younger (11) because the structural properties of the patella-patellar tendon-tibia complex are believed to deteriorate with age. Although several studies have specifically examined properties of

the human patellar tendon and patella-patellar tendon-tibia complex (1-4,11,19,21), clear evidence of age-related changes has not been established. Because significant age-related deterioration has been identified in the human femur-anterior cruciate ligament-tibia complex (20,26), the patellar tendon is presumed to undergo such changes.

The failure mode of patella-patellar tendon-tibia complexes also may contribute to the decision to use donors 55 years of age and younger. Haut et al. (11) found no apparent age-related differences in stiffness, elongation at failure, or failure load among specimens that failed within the tendon substance (age of donors, 16-44 years). Patellar tendon specimens from donors aged 61-65 years, however, all failed by bone avulsion (11). Butler et al. (3) found that failure of patella-patellar tendon-tibia complexes occurred within the tendon substance for specimens from donors 21-30 years old.

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Address correspondence and reprint requests to Dr. S. L-Y. Woo at Department of Orthopaedic Surgery, 1010 Lilliane S. Kaufmann Building, University of Pittsburgh, 3471 Fifth Avenue, Pittsburgh, PA 15213, U.S.A.

Recently, the viscoelastic response of patellar tendon grafts to cyclic loads has been investigated. Graf et al. (9) studied the primate patellar tendon and found that significantly less stress-relaxation occurred if cyclic, rather than static, preconditioning was performed. A previous study in our laboratory used quasilinear viscoelasticity to describe the viscoelastic behavior of the human patellar tendon and compared the results with similar data for the anterior cruciate ligament (17). This theoretical approach allows direct comparison between the viscoelastic properties of different tissues. During a stress-relaxation test, the initial stress for both the patellar tendon and the anterior cruciate ligament decreased by a similar amount: 80% of the original value after 1 hour.

The objectives of the present study were to measure the tensile and viscoelastic properties of patellar tendon specimens from younger and older age groups. Stress-relaxation, cyclic stress-relaxation, and uniaxial tensile load to failure tests were performed on specimens of human patellar tendon to determine whether these properties differed significantly between younger and older specimens. To ensure that the specimen would fail in the tendon substance, the specimen was cut to a small cross-sectional area (15 mm^2) and a special clamping system was developed and used. As a result, values for stress-relaxation, ultimate tensile strength, strain at failure, modulus, and strain energy density of the patellar tendon substance could be determined and compared.

MATERIALS AND METHODS

Thirty fresh-frozen, nonirradiated, human knees were obtained from Lifenet Tissue Services (Pittsburgh, PA, U.S.A.), the Willed Body Program of Texas (Galveston, TX, U.S.A.), and the Humanity Gifts Registry Program of Pennsylvania (Philadelphia, PA, U.S.A.). The specimens were separated by age of the donor into two groups of 15 each: a younger group, 29-50 years old, and an older group, 64-93 years old. To avoid dependence effects in the statistical analysis, unpaired specimens were used.

The patella-patellar tendon-tibial tubercle complex was removed from each knee with use of an oscillating saw. Each complex was cut into lateral, central, and medial portions with its accompanying bone blocks (each block was approximately $1 \times 1 \times 3 \text{ cm}$). Only the central third of the bone-tendon-bone complex, the portion most commonly used for grafts, was taken. Each bone block and its insertion

site was embedded in polymethylmethacrylate. A Kirschner wire was drilled through each block, perpendicular to the longitudinal axis of the tendon, to help maintain alignment of the tendon while the polymethylmethacrylate cured. Proper alignment of the tendon and reinforcement with a Kirschner wire helped to provide better gripping of the specimen during tensile testing. To minimize tissue damage from exothermic polymerization and thus help to prevent premature failure during tensile testing, the polymethylmethacrylate was allowed to cure inside a freezer. After the polymethylmethacrylate had cured, the patellar tendon substance was wrapped in saline-soaked gauze and the complex was stored in double plastic bags inside a freezer (-20°C) for no more than 48 hours. During the entire preparation of the specimen, the tendon substance was kept moist with saline.

On the day of testing, the specimens were thawed at room temperature and placed in specially designed clamps (Fig. 1A). The tendon substance was trimmed carefully to a width of 5 mm (resulting in a cross-sectional area of approximately 15 mm^2) to promote substance failure during tensile testing. The cross-sectional shape and area of the patellar tendon were measured with a laser micrometer system (18), with the specimen under minimal tension of approximately 1 N. The laser micrometer is a microprocessor-controlled device that sends a collimated scanning laser beam from a transmitter to a receiver. The specimen is placed in the path of the laser beam and is rotated in 3° increments while the widths of the shadows cast onto the receiver are measured. With use of these data, the image is reconstructed and the cross-sectional area is calculated. Lee and Woo (18) showed that the laser micrometer system can measure the cross-sectional area of soft tissues such as ligaments and tendons to within an accuracy of 5%. In the present study, the patellar tendon area was measured just above the tibial bone block, where failure usually occurred in preliminary tests. Prior to testing, three dye lines (Verhoeff's elastin stain), spaced about 9 mm apart, were placed across the width of the tendon, perpendicular to the longitudinal axis (Fig. 1B), to facilitate strain measurement. Substance strain was measured by means of a video dimension analyzer system (5,21,25). A video recorder was used to transmit the specimen's image onto a monitor. The video dimension analyzer then projected a window over two of the dye lines and converted the distance between them into an output voltage, which in turn was converted to strain with

A, B

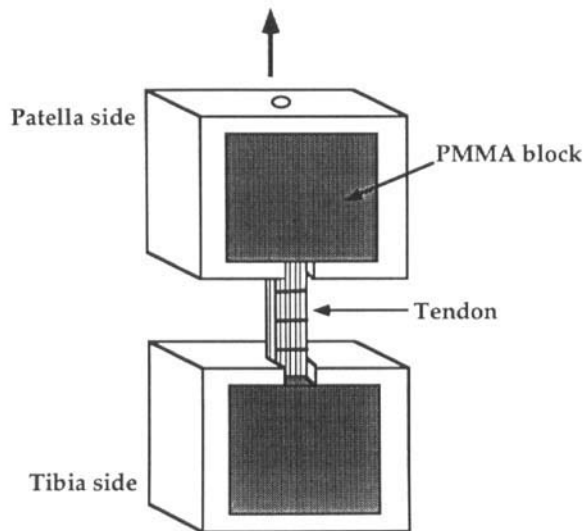
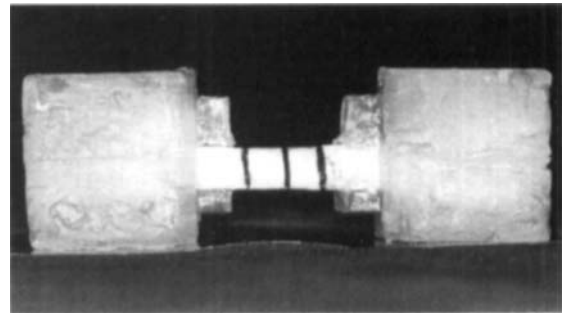


FIG. 1. A: Schematic of the bone-tendon-bone complex in specially designed clamps. PMMA = polymethylmethacrylate. **B:** Photograph of patellar tendon specimen with polymethylmethacrylate bone cement blocks and dye lines.

use of a strip chart recorder. Errors in linearity and accuracy have been determined to be less than 0.5% for this system (25).

The bone-patellar tendon-bone preparation and clamps were submerged in a saline bath at 37°C and were mounted in a materials testing machine (model 4502; Instron, Canton, MA, U.S.A.). A minimum of 10 minutes was allowed for equilibration of temperature. Initially, a load of 1 N was applied, and the clamp-to-clamp distance was measured as initial gauge length (defined as zero). The specimens then were preconditioned by cyclic extension from 0 to 2% of the initial gauge length for 10 cycles, to give each specimen a uniform strain history. After preconditioning, the specimens remained in an unloaded state for 30 minutes to minimize viscoelastic effects (9,13). Two stress-relaxation tests then were used to examine viscoelastic response in both the toe and linear regions. In the first test, the specimens were stretched at 100 mm/min to a stress level of 1 MPa and were held at the resulting elongation for 15 minutes. The second stress-relaxation test followed the same procedure as the first, except that the stress level was increased to 4 MPa. A 30-minute rest period followed each test. Next, the specimens were cyclically extended between the two elongations obtained in the stress-relaxation tests, for 15 cycles at a rate of three cycles/min. After another 30-minute rest period, the specimens were stretched at an elongation rate of 200 mm/min until failure occurred. The failure mode was recorded for each specimen.

Load versus elongation data for each test were recorded with use of a strip chart recorder. All tests

were videotaped to allow strain analysis with the video dimension analyzer system. With use of the previously measured cross-sectional area of the specimens, tensile stress (MPa) was calculated to obtain stress-relaxation and stress-strain curves. The amount of stress-relaxation was determined from the stress-relaxation curves. Ultimate tensile strength, strain at failure, modulus (defined as the slope between 6 and 7.5% strain), and the strain energy density (area beneath the stress-strain curve) were determined from the stress-strain curves.

Quasilinear viscoelasticity (8) was used to model the viscoelastic properties of the patellar tendon tissue. Our laboratory and others previously have used this theory to describe the behavior of ligaments and tendons (10,17,19,23,24). Quasilinear viscoelasticity allows a quantitative comparison of the stress-strain behavior of ligaments and tendons in terms of five constants. The constants are determined by nonlinear least-squares curve-fits to data from the stress-relaxation and tensile load to failure experiments. To confirm their values, the constants are used to predict loads in separate experiments on cyclic elongation.

The parameters C , τ_1 , and τ_2 from the reduced relaxation function, $G(t)$, were determined from curve-fits of stress-relaxation data. These values were used in the curve-fit of the elastic stress-strain curve to find A and B , the other two material parameters. The physical significance of these parameters was discussed by Sauren and Rousseau (22). The tissue becomes more elastic with decreasing values of C , and the time constants τ_1 and τ_2 govern fast and

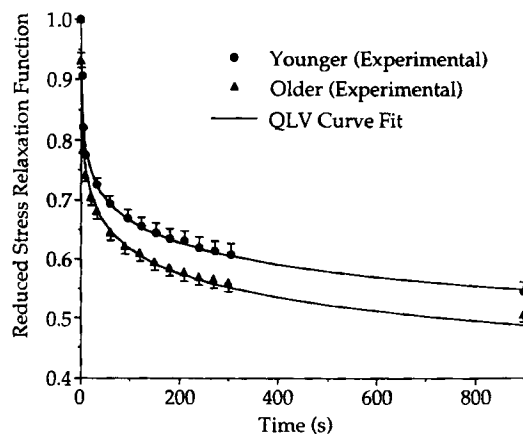


FIG. 2. The reduced stress-relaxation function (mean $\pm$ SEM) for both the younger and older groups at 4 MPa of initial stress. QLV = quasilinear viscoelasticity.

slow viscous phenomena, respectively. The parameter combination AB determines the initial slope of the elastic stress-strain curve, and B influences its nonlinearity. In this study, all five parameters were independently confirmed by matching of the predicted peak and valley stresses to the corresponding results from our cyclic stress-relaxation test.

Data were analyzed with use of a one-way analysis of variance to detect significant ($p < 0.05$) differences between the age groups for stress-relaxation after 15 minutes, cyclic stress-relaxation after 15 cycles, ultimate tensile strength, strain at failure, modulus, and strain energy density. Preliminary studies showed that ultimate tensile strength had the largest SD of the measured variables. A power analysis estimated that, at a significance level of $p < 0.05$, 15 specimens in each age group were required to detect a minimum difference of 15 MPa in ultimate tensile strength.

RESULTS

In both age groups, the reduced stress-relaxation functions (current stress divided by initial stress) were similar for both the 1 and 4 MPa initial stress tests. The reduced stress-relaxation function for the two age groups, with 4 MPa initial stress, was used to curve-fit the data with use of quasilinear viscoelasticity, from which the constants C , τ_1 , and τ_2 were determined (Fig. 2). Equations for the reduced relaxation functions are given by $G(t) = 0.91 - 0.053 \ln(t)$ for the younger group and $G(t) = 0.94 - 0.057 \ln(t)$ for the older group. The quasilinear viscoelasticity parameters were $C = 0.32$, $\tau_1 = 0.35$, and $\tau_2 = 2.1(10^6)$ for the younger group and $C = 0.68$, $\tau_1 = 0.60$, and

$\tau_2 = 5.03(10^6)$ for the older group. The younger group experienced a $46 \pm 9\%$ (mean $\pm$ SD) decrease in stress after 15 minutes, whereas the older group exhibited a $50 \pm 6\%$ decrease. The difference between these values was not statistically significant.

Averaged stress-strain curves for patellar tendons from both age groups exhibited the nonlinearity characteristic of ligaments and tendons (Fig. 3). The transition from toe (initially low but increasing modulus) to linear regions (constant modulus) appeared to occur at about 2% strain. The nonlinearity of the toe region may represent the recruitment of collagen fibers, with the linear region representing the elastic response of the collagen fibers in tension. All specimens failed within the tendon substance near the tibial insertion. Values for ultimate tensile strength and strain at failure for the younger group were

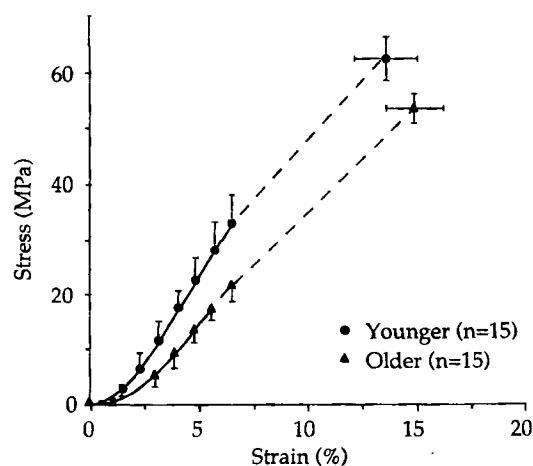


FIG. 3. Stress-strain curves (mean $\pm$ SEM) for both the younger and older age groups.

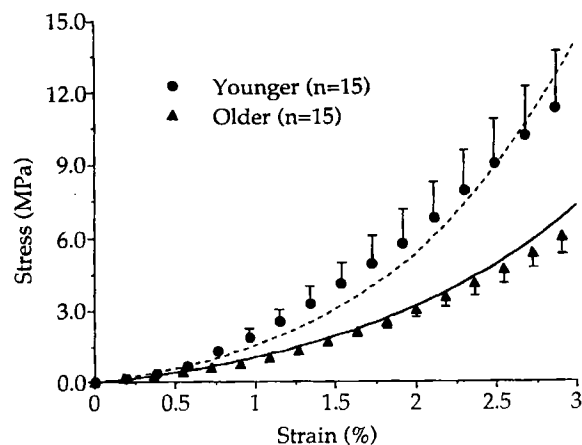


FIG. 4. Stress-strain data (mean $\pm$ SEM): experimental and quasilinear viscoelasticity theory.

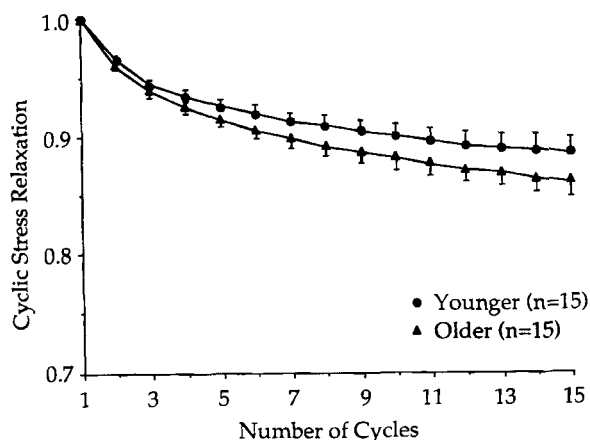


FIG. 5. Cyclic stress-relaxation (mean $\pm$ SEM) for both younger and older age groups. (Data normalized with use of initial peak stress.)

64.7 ± 15.0 MPa and $14 \pm 6\%$, respectively. For the older group, the corresponding values were 53.6 ± 10.0 MPa and $15 \pm 15\%$. Ultimate tensile strength for the older group was significantly less ($p < 0.05$) than that for the younger group, but strain at failure was not significantly different. Modulus values were 660 ± 266 MPa for the younger group and 504 ± 222 MPa for the older group; the difference was not statistically significant. Strain energy density was 4.33 ± 2.5 MPa for the younger group and 3.68 ± 1.62 MPa for the older group; again, there was no statistically significant difference. Curve-fits to the stress-strain data of as much as 3% strain resulted in values for A and B of 1.5 and 54.0 for the younger group and 1.5 and 41.1 for the older group (Fig. 4).

During cyclic stress-relaxation, peak stress values decreased by $12 \pm 5\%$ and $14 \pm 5\%$ in the younger

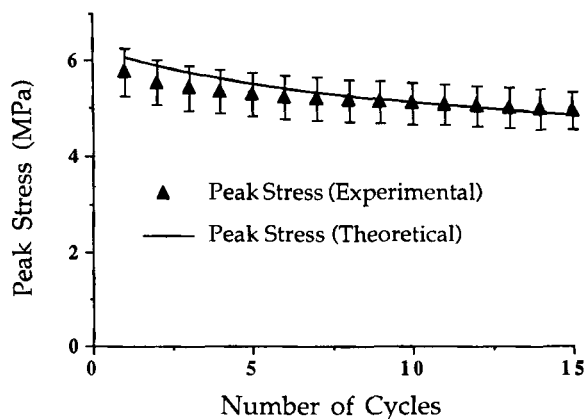


FIG. 6. Predicted (quasilinear viscoelasticity theory) and measured (experimental) peak cyclic stresses (mean $\pm$ SEM) for the older age group ($n = 15$).

and older groups, respectively (Fig. 5). Differences between the groups were not statistically significant. The viscoelastic parameter values as determined from stress-relaxation and stress-strain data are used to predict the response of the specimen to cyclic elongation. Since the cyclic test is not used to find the parameter values, failure of the parameters to describe the cyclic response indicates that either the model is inappropriate or the parameter values do not accurately describe the viscoelastic behavior of the specimen. Fortunately, the theoretical predictions matched the measured values of peak cyclic stresses quite closely (Fig. 6).

DISCUSSION

Our study was designed to assess differences in viscoelastic and mechanical properties of human patellar tendons from younger and older humans. Our data suggest that there are only minimal differences in the tensile properties of the patellar tendon substance between the two groups. Comparisons of stress-relaxation, ultimate tensile strength, strain at failure, modulus, and strain energy density revealed that only ultimate tensile strength differed significantly between younger and older groups. Quasilinear viscoelasticity was curve-fit to average stress-relaxation and stress-strain curves to illustrate its use as a tool for comparison of viscoelastic behaviors. The curve-fits suggest differences in time-dependent behavior between the younger and older groups. On the basis of the difference in B (which influences nonlinearity of the stress-strain response), younger specimens appear to exhibit more nonlinear behavior, resulting in higher loads at lower levels of elongation. Differing values of C (a measure of elasticity) indicate that the younger specimens have a more elastic stress-strain response; this suggests that they dissipate less energy and have a shorter recovery time upon removal of load. On the basis of the percentage stress-relaxation, however, age did not have a significant effect on the viscoelastic properties of the patellar tendon substance.

Viscoelastic behaviors such as creep and cyclic stress-relaxation are important to describe the response of ligaments and tendons to loads during walking and other daily activities. The viscoelastic response also is critical for preconditioning and initial tensioning of grafts. The importance of these complex time-dependent behaviors is clear, but evaluation and comparison of the viscoelastic properties of tissues is difficult without mathematical tools such as quasilinear viscoelasticity. The parameters within

TABLE 1. Summary of failure properties for human patellar tendon

Reference	Age range (yrs.)	No. of specimens	Cross-sectional area (mm ²)	Modulus (MPa)	Ultimate tensile strength (MPa)	Strain at failure (%)	Strain energy density (MPa)
Current study (younger group) ^a	29-50	15	14.6 ± 0.3	660 ± 266	64.7 ± 15.0	14 ± 6	4.33 ± 2.5
Haut and Powlison (12) ^b	20-44	6	76	307 ± 17	43.7 ± 3.9	23.3 ± 1.4	
France et al. (6) ^a	24-62	15		121 ± 37	47.4 ± 16.3	17 ± 5	
Butler et al. (3) ^{b,c}	21-30	5	1.20 ± 0.3	643 ± 53	68.5 ± 6	13.5 ± 7	5.03 ± .07
		8	1.86 ± 0.3				
		6	1.65 ± 0.2				
Butler et al. (2)	26 ± 6	7	50.5	305.5 ± 59.0	58.3 ± 6.1	26.5 ± 29	9.9 ± 1.9
Noyes et al. (21) ^b							
Current study (older group) ^a	64-93	15	14.8 ± 0.2	504 ± 222	53.6 ± 10.0	15 ± 5	3.7 ± 1.6

^a Data are given as mean ± SD.^b Data are given as mean ± SEM.^c Specimens from three donors.

quasilinear viscoelasticity represent not merely the amount of stress-relaxation at a given time but also the shape of the stress-relaxation and stress-strain curves. Thus, quasilinear viscoelasticity provides parameters that can be used for relatively simple comparison of complex viscoelastic behaviors.

A unique aspect of the work presented here is the use of two stress-relaxation tests. The values of 1 and 4 MPa were chosen for the stress-relaxation tests so that the first test would produce a maximum stress from the toe region of the stress-strain curve and the second would produce a maximum stress near the lower end of the linear region of the stress-strain curve. The two tests were used to determine whether there are different relaxation behaviors in the two regions, because it often is tacitly assumed that the relaxation behavior is the same. This assumption appears questionable, since the mechanism responsible for generating stress is thought to be different in the two regions. However, our results showed that no differences in the relaxation properties could be demonstrated statistically, thus validating the assumption for the human patellar tendon.

It should be noted that our data cannot be applied directly to the structural properties of the patella-patellar tendon-tibia complex. Properties of the insertion sites, tendon size and geometry, and tissue shape all play a role in determination of the structural properties of patellar tendon grafts. Although graft size can be controlled in surgery, the properties of the insertion sites cannot. Therefore, age-related changes in the properties of the osseous insertion sites must be further investigated. The data that we have presented are focused on mechanical proper-

ties of the patellar tendon substance rather than on structural properties of the patella-patellar tendon-tibia complex. Although it is clear that the mechanical properties of cancellous bone deteriorate with age, differences in the properties of patellar tendon substance from younger and older donors are not as well established. Ultimately, these properties could influence the behavior of a graft as much as the established differences in cancellous bone properties. We emphasize that it is not merely failure loads with which we are concerned but also the low-load performance and time-dependent viscoelastic properties of the tendon substance and the associated complex. These properties are likely to be more relevant to daily activity and long-term integrity of the graft than its mechanical performance at high near-failure loads.

The use of two discrete groups in this study was necessitated by the limited number of available specimens. Although it would be preferable to test specimens from donors within a range of ages, the number of specimens required to establish a statistically significant correlation between age and any tensile or viscoelastic properties was simply too large to be practical. The use of two age groups for a bimodal comparison, with the older group being older than the currently accepted age for allograft donors, provided the best chance to discover a difference between the groups.

The results of the stress-relaxation and cyclic stress-relaxation tests were similar to those previously reported (9,19). For example, the decrease in initial stress during our cyclic test was 13% after 5 minutes, consistent with the 16% decrease after 5

minutes of cyclic elongation measured by Lyon et al. (19). Graf et al. (9) found, as we did, that more stress-relaxation occurs with a constant deformation applied to the tissue than with a cyclic deformation. We also have shown, based on the similarity in results for the 1 and 4 MPa initial stresses, that the stress-relaxation response appears to be relatively independent of applied load over the lower range of levels of stress used in the experiments.

Comparison of the measured tensile properties of human patellar tendons reveals that the data on modulus and ultimate tensile strength from the current study are in agreement with those of Butler et al. (3). However, these values are not consistent with data from other studies, as shown in Table 1 (3,6,12). We believe that part of the difference may be attributed to the method of cross-sectional area measurement or differences in cross-sectional area of the specimens. One group of investigators used calipers and assumed a rectangular cross-sectional shape (11,12), whereas others used a constant pressure micrometer (2,3). In addition to the errors in measurement associated with these devices, actual differences in area (Table 1) also produce differences in measured modulus and ultimate tensile strength and are certainly responsible in part for the differences in measured parameters. Specimens with larger cross-sectional areas experience a less uniform load, resulting in lower measured moduli and ultimate tensile strengths. Although differences in cross-sectional area are partly responsible for the differences observed in Table 1, the testing environment and differences in strain measurement also may influence the results of mechanical tests. For example, specimens tested in a saline bath have a higher modulus and greater ultimate tensile strength but lower values for strain at failure than specimens tested in a saline drip environment (12). The location chosen for strain measurement (midsubstance, clamp-to-clamp, and so on) also can have significant effects on modulus values (25).

Although it is known that the mechanical properties of the human femur-anterior cruciate ligament-tibia complex (20,26) and anterior cruciate ligament (20) change significantly with age, our results show minimal effects of age on the mechanical properties of the patellar tendon substance. This lack of age-related change may be due to the consistently larger loads placed on the patellar tendon. Korvick et al. (15,16) recently showed, in goats, that functional demands on the anterior cruciate ligament and patellar tendon are different. They demonstrated that the

patellar tendon is loaded more than the anterior cruciate ligament during daily activity. These larger loads might prevent weakening of the patellar tendon with age if the tissue adapts mechanically in response to the applied stress.

We have noted that our data cannot be applied directly to determination of the clinically important properties of the patella-patellar tendon-tibia complex. However, our results are of fundamental interest in that they establish the mechanical similarity of tendon substance from older and younger donors. Observed differences in the bone-patellar tendon-bone complexes between the two groups thus may be attributed to differences in the cancellous bone. Attempts to evaluate graft material nondestructively prior to implantation and to establish a higher upper age limit for graft donors should, on the basis of the data presented here, focus on the insertion sites and the bone components of the complex.

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