Region-specific mechanical properties of the human patella tendon

B. T. Haraldsson, P. Aagaard, M. Krogsgaard, T. Alkjaer, M. Kjaer, and S. P. Magnusson

Institute of Sports Medicine, Bispebjerg Hospital, Copenhagen; Institute of Sports Exercise and Clinical Biomechanics, University of Southern Denmark, Odense; Orthopedic Department, Bispebjerg Hospital, Copenhagen; and Laboratory for Functional Anatomy, Biomechanics and Motor Control, Institute of Medical Anatomy, The Panum Institute, University of Copenhagen, Copenhagen, Denmark

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Haraldsson, B. T., P. Aagaard, M. Krogsgaard, T. Alkjaer, M. Kjaer, and S. P. Magnusson. Region-specific mechanical properties of the human patella tendon. J Appl Physiol 98: 1006–1012, 2005. First published September 24, 2004; doi:10.1152/japplphysiol.00482.2004.—The present study investigated the mechanical properties of tendon fascicles from the anterior and posterior human patellar tendon. Collagen fascicles from the anterior and posterior human patellar tendon in healthy young men (mean ± SD, 29.0 ± 4.6 yr, n = 6) were tested in a mechanical rig. A stereoscopic microscope equipped with a digital camera recorded elongation. The fascicles were preconditioned five cycles before the failure test based on pilot data on rat tendon fascicle. Human fascicle length increased with repeated cycles (P < 0.05); cycle 5 differed from cycle 1 (P < 0.05), but not cycles 2–4. Peak stress and yield stress were greater for anterior (76.0 ± 9.5 and 56.6 ± 10.4 MPa, respectively) than posterior fascicles (38.5 ± 3.9 and 31.6 ± 2.9 MPa, respectively), P < 0.05, while yield strain was similar (anterior 6.8 ± 1.0%, posterior 8.7 ± 1.4%). Tangent modulus was greater for the anterior (1,231 ± 188 MPa) than the posterior (583 ± 122 MPa) fascicles, P < 0.05. In conclusion, tendon fascicles from the anterior portion of the human patellar tendon in young men displayed considerably greater peak and yield stress and tangent modulus compared with the posterior portion of the tendon, indicating region-specific material properties.

collagen fascicle; stress; strain

Athletes who participate in sports that require jumping activities, such as in volleyball, are particularly susceptible to patellar tendinopathy (11, 22, 31). Jumping activities appear to impose considerable forces on the knee extensor mechanism (12, 31), and, although the etiology of patellar tendinopathy remains elusive, it is possible that the magnitude of loading of the patellar tendon may be an important factor. In fact, a recent report showed that volleyball players with patella tendinopathy have greater body weight, strength trained more, and displayed superior jump performance compared with an asymptomatic cohort (23). Furthermore, greater ground reaction forces and rates of knee extensor loading appear to be related to patellar tendinopathy (31).

Imaging findings suggest that patellar tendinopathy mostly concerns the proximal and posterior portion of the patellar tendon (19, 34). However, very few studies have examined the mechanical properties of the anterior compared with the posterior portion of the human patellar tendon. Almekinders et al. (2) investigated the strain pattern in patellar tendons instrumented with strain gauges on the anterior and posterior side of the patellar tendon in human cadaver knees. The data show that, during quadriceps loading, tensile strain was uniform in the anterior and posterior region with the knee in full extension. However, with knee flexion tensile, strain increased on the anterior side but decreased on the posterior, and, therefore, the authors suggested that the posterior portion of the tendon may not be subjected to great loads in the functional flexion range and are, consequently, stress shielded. Those findings were sharply contrasted by those of Basso et al. (4), who showed that quadriceps loading of cadaver knees in flexion caused a greater strain on the posterior compared with the anterior side of the patellar tendon. Thus the currently available data on strain properties of the anterior and posterior portion of the human patellar tendon are sparse and conflicting (2, 4) and, moreover, are based on older (~59 and 73 yr) cadaver specimens that may not necessarily reflect the tendon properties of younger persons who are typically afflicted with the condition.

In addition to determining strain properties of the whole tendon, Basso et al. (4) measured the material properties of isolated bundles from the anterior and posterior patellar tendon and showed that the anterior fiber bundles displayed greater strain than that of the posterior bundles (4). However, the strain values were sizeable (15–22%), whereas the stress (22–23 MPa) and modulus (122–180 MPa) were substantially lower than previously reported for the human tendon (6, 24, 37).

It is well known that applied preconditioning protocol (14, 32, 36) and the estimation of tissue strain based on grip-to-grip elongation compared with that based on midsubstance optical surface markers can appreciably influence the measurement of mechanical properties of tendon tissue (6, 9, 10, 37, 38). However, there is a paucity of data concerning the influence of these factors on small-tendon tissue samples. Specifically, the influence of strain measurement techniques and preconditioning cycles has never been investigated in isolated human collagen fascicles.

Based on the location of the injury, we hypothesized that the mechanical properties of the anterior collagen fascicles exceeded those of the posterior collagen fascicles of the human patellar tendon. The purpose of the present study was thus to compare the material properties of collagen fascicles from the anterior and posterior portion of the patellar tendon in healthy young men. Furthermore, we sought to examine the effect of preconditioning cycles on fascicle length and to evaluate tissue deformation based on grip-to-grip displacement and that of optical surface markers.

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MATERIALS AND METHODS

Tissue specimens. To develop and assess the method of the mechanical testing and the data recording procedures of individual strands of collagen fascicles, tissue specimens from a mature 3-month-old rat tail were used. A section of ~25 mm was cut from the proximal end of the skinned rat tail. Single strands (n = 14) of collagen fascicles [diameter (ø) 400–600 μm] were then teased out and placed in saline-soaked gauze and stored at −20°C. On the test day, the specimens were allowed to thaw while immersed in isotonic saline solution for 30 min at room temperature. The initial investigations on rat tail fascicles (see Preliminary data on rat tail fascicles) were subsequently followed by experiments on human tissue.

To examine whether collagen fascicles from the anterior and posterior human patella tendon differed with respect to their material properties, tissue specimens were obtained from healthy young men (mean ± SD, 29.0 ± 4.6 yr, n = 6) during elective anterior cruciate ligament reconstruction. Informed consent was obtained from all subjects. During surgery, the middle third of the patella tendon was harvested and used for the ligament reconstruction (28). Thin collagen bundles that were ~35 mm in length and ~3.5 mm in diameter were obtained from the anterior and posterior portion of the harvested tendon. From these collagen bundles, individual strands of fascicles (ø 300–400 μm) were dissected under a stereoscopic microscope (see below), placed in saline-soaked gauze, and stored at −20°C. One fascicle was obtained from the anterior portion of the tendon, and one fascicle from the posterior portion of the tendon. On the test day, the specimens were allowed to thaw immersed in saline solution for 30 min at room temperature. The human tissue specimens were all obtained from patients who, at the time of elective surgery, had full range of knee motion and were able to perform normal activities of daily living without any symptoms, but were unable to participate in sports secondary to knee instability.

Instrumentation. The custom-made mechanical test rig consisted of a 1-kg strain-gauge transducer (Pioden Controls Limited, Canterbury, UK), specimen chamber, and a motorized spring-loaded linear variable differential transformer (LVDT) (RDP Electronics, Wolverhampton, UK) that achieved and measured changes in grip displacement at a predetermined velocity (Fig. 1A). The strain-gauge transducer displayed linearity from 0 to 1,000 g, with a 0.16% accuracy, and the LVDT had a resolution of <0.1 μm.

The mechanical test frame was placed under a stereoscopic microscope (SMZ1000, Nikon, Tokyo, Japan) with a C-mount lens (×0.38). The microscope was equipped with a 15-Hz digital camera (DFW-X700, Sony, Tokyo, Japan) with a 1,024 × 768 output signal format. Synchronization of force and displacement data and video data was achieved with a light diode placed in the viewing field of the

Fig. 1. A: setup with the stereoscopic microscope mounted with a 15-Hz digital camera. B: small-scale tensile testing device that is placed under the microscope in A. Note the fascicle with ink marks mounted on the specimen plates and its crimped appearance, which disappears during tensile loading. A/D, analog-to-digital.
microscope. The digital video (15 Hz) and the force and displacement data (20 Hz) were simultaneously sampled via a 16-bit analog-to-digital converter (PowerLab/8sp, ADInstruments, Castle Hill, Australia) and stored on a personal computer for subsequent analysis (Fig. 1B).

Mechanical testing procedures. Approximately 5 mm of each end of the single collagen strand were allowed to air dry at room temperature. Thereafter, the dried fascicle ends were glued to the uncoated aluminum end plates of the mechanical rig (see below) with cyanoacrylate glue. The glue was allowed to dry while the middle portion was kept in saline-soaked gauze. After the glue was dry, ink marks were placed in either end of the specimen ~3 mm away from the end plates to serve as landmarks for recording of midsubstance deformation. The fascicles and end plates were submerged in a Petri dish with 0.9% saline solution before testing, which was started 15 min thereafter. It should be noted that pilot trials with the commonly used Verhoff’s stain repeatedly produced specimen failure at relatively low stresses at the very location of the stain mark (data not published).

The rat tail fascicles underwent eight “preconditioning” displacement cycles at a displacement rate of 0.07 mm/s of the LVDT to a separately determined stress of 3–4 MPa interspersed with 1-min intervals (Fig. 2). One minute thereafter, the specimen was loaded to failure at a strain rate of 0.13 mm/s (cycle 9). The eight preconditioning cycles were subsequently analyzed (n = 6) based on plate-plate displacement to determine the number of cycles to use to get reproducible force-length data (see Preliminary data on rat tail fascicles).

Based on the results of the rat tail fascicles, the human fascicles were preconditioned to a stress of ~3–4 MPa for a total of five cycles at a displacement rate 0.07 mm/s of the LVDT before failure in cycle 6 at a strain rate of 0.13 mm/s. These preconditioning cycles were also analyzed (n = 5) to ensure that the force-length data were reproducible (see RESULTS).

Data reduction and analysis. The cross-sectional area of the fascicles was calculated based on the measured diameter of the fascicles, assuming that the fascicles were circular. The diameter was measured in the experimental setup with the use of the stereoscopic microscope, while the specimen was submerged in the saline at three locations along the length of the specimen, and an average of the three measures was used.

Custom-made software was used to analyze the data. Fascicle stress was calculated as the tensile force (N) divided by the cross-sectional area (m²) of the fascicle and reported as megapascals. Least squares linear regression analysis was performed on the curve portion with a tangential slope (i.e., point-to-point slope) of 85.5–100% of peak tangential slope (Fig. 3), which yielded a correlation coefficient that exceeded r = 0.99 (P < 0.0001) in all instances. Yield stress was defined as the instant when the difference between recorded force and the extrapolated linear regression line exceeded 0.85 MPa (see Fig. 3A). The linearity phase never overlapped the yield phase, i.e., in all cases the yield point occurred outside (rightward to) the linear regression interval. The tangent modulus was calculated in the linear portion of the stress-strain curve. On all occasions, the fascicle specimens ruptured in between but near the end plates of the mechanical rig (see Fig. 1A). Therefore, it was deemed that midsubstance strain could only be reasonably calculated up to yield stress. For the analysis of ink marks on the video sequences, two-dimensional coordinates were reconstructed by direct linear transformation using the Ariel Performance Analysis System (Ariel Dynamics, San Diego, CA). The position data were digitally low-pass filtered by a fourth-order zero-lag Butterworth filter with a cutoff frequency of 2 Hz. A second-order polynomial fit (r = 0.93 ± 0.02, mean ± SE) was applied to obtained data for calculation of modulus (Fig. 3B). Consequently, the following parameters were obtained: fascicle peak stress, fascicle yield stress, fascicle strain at yield stress, and tangent modulus. Two fascicles from the anterior portion of the tendon exceeded the capabilities of the mechanical test device by reaching stresses >100 MPa without fracturing and thus contributed to an underestimation of peak stress for the anterior fascicles.

Friedman tests with subsequent Wilcoxon rank tests were used to examine whether there was a difference between repeated cycles in the rat tail fascicles. In addition, Spearman’s correlation coefficient and coefficient of variation for duplicate measures were used to examine reproducibility. Wilcoxon signed-rank tests were used to examine whether there was a difference between the anterior and posterior fascicles of the human patellar tendon. Results are reported as means ± SE.

Preliminary data on rat tail fascicles. Fascicle length (plate-plate) changed significantly with cycles (P < 0.001): cycle 8 differed significantly from cycles 1–5 (P < 0.05), but not cycles 6 and 7 (Fig. 4, A and B). The correlation coefficient for length in cycle 6 vs. 7 was r = 1.0, with a corresponding coefficient of variation for duplicate measures of 3%. Fascicle peak stress and tendon modulus were

Fig. 2. Complete preconditioning cycle of a rat tail fascicle. A: length change of the fascicle (plate-plate) normalized to onset of force; B: stress of the fascicle. C: relationship between stress and length change for both the ascending and descending portion of the cycle.
33.0% / H11006
the posterior fascicles (38.5% / H11006) changed significantly with cycles (2–4 / H11006). Strain was also similar for the anterior (12.4% / H11006) and posterior fascicles (13.0% / H11006) based on plate-plate measurements. Midsubstance strain was lower and modulus greater than that obtained from plate-plate measurement, $P < 0.05$ (see Table 2).

RESULTS

13.0 ± 0.6 and 725 ± 62 MPa, respectively. Fascicle strain at yield stress was 4.3 ± 0.1% based on plate-plate measures and 2.6 ± 0.1% based on midsubstance measures, $P < 0.001$.

**Fig. 3.** A: stress-strain relationship for a human patella fascicle. Dashed line, linear portion of the relationship; △, identified yield stress and peak stress. B: stress-strain relationship based on plate-plate and midsubstance (from ink marks) strain. Note the markedly reduced midsubstance strain, which yields a substantial increase in strain and modulus (see Table 1 and 2). $L$, length; $L_o$, initial fascicle length.

13.0 ± 0.6 and 725 ± 62 MPa, respectively. Fascicle strain at yield stress was 4.3 ± 0.1% based on plate-plate measures and 2.6 ± 0.1% based on midsubstance measures, $P < 0.001$.

**RESULTS**

**Human patellar tendon fascicles.** Fascicle length (plate-plate) changed significantly with cycles ($P < 0.05$): cycle 5 differed significantly from cycle 1 ($P < 0.05$), but not cycles 2–4 (Fig. 4, C and D). The correlation coefficient for length in cycle 2 vs. 3 was $r_s = 0.9$, with a corresponding coefficient of variation for duplicate measures of 8%. The diameters for the anterior fascicles ($\phi$ 320 ± 30 $\mu$m) and posterior fascicles ($\phi$ 330 ± 30 $\mu$m) were similar (mean difference: 20 ± 20 $\mu$m). Peak stress was greater for the anterior (76.0 ± 9.5 MPa) than the posterior fascicles (38.5 ± 3.9 MPa), $P < 0.05$. Yield stress was significantly greater for the anterior (56.6 ± 10.4 MPa) than the posterior fascicles (31.6 ± 2.9 MPa), $P < 0.05$. Yield strain (midsubstance) did not differ between the anterior (6.8 ± 1.0%) and the posterior fascicles (8.7 ± 1.4%). Strain was also similar for the anterior (12.4 ± 1.4%) and posterior fascicles (13.0 ± 1.0%) based on plate-plate measurements. Midsubstance strain was lower and modulus greater than that obtained from plate-plate measurement, $P < 0.05$ (see Table 2).

**DISCUSSION**

The main findings of the present study are that tendon fascicles from the anterior portion of the human patellar tendon in young men displayed greater peak and yield stress and tangent modulus compared with the posterior portion of the tendon, indicating region-specific material properties. Moreover, it was demonstrated that a preconditioning protocol yielded consistent data beyond five cycles in rat tail fascicles and similarly beyond one cycle in fascicles from the human patellar tendon. To our best knowledge, these are the first reported data on material properties of human collagen fascicles obtained from healthy young men.

Patellar tendinopathy chiefly concerns the posterior portion of the patellar tendon (19, 34), but there are limited investigations into region-specific mechanical properties of the patellar tendon. Almekinders et al. (2) and Basso et al. (4) have reported conflicting patellar tendon strain properties in human cadaver models, which may be due to methodological differences. Basso et al. also examined the material properties of the anterior and posterior patellar tendon and showed that the posterior fiber bundles exhibited greater strain properties, while maximum stress of modulus did not differ. In contrast, the data of the present study show that, whereas the strain properties are similar, the yield and peak stress and tangent modulus of the anterior collagen fascicles far exceeded those of the posterior collagen fascicles obtained from young, healthy men.

Basso et al. (4) reported a maximum stress of ~22 MPa for the anterior bundles, whereas the present study obtained a maximum stress of ~76 MPa. This marked difference in absolute magnitude of stress may be due to age (79 vs. 29 yr). Furthermore, Basso et al. reported maximum strain values of 15% for the anterior bundles. The present study reported corresponding strains of 7% up to the yield stress, which is similar to that reported for the free Achilles tendon (8%) in vivo (24). It is possible that these differences can be accounted for by the grip-grip measurement used by Basso et al. (4) compared with the midsubstance measurement technique used in the present study (see RESULTS and see below). Alternatively, the difference in absolute magnitude may be ascribed to differences in strain at different hierarchical levels or size of the tendon (3, 13), i.e., a bundle of collagen (22 mm²) (4) would strain to a greater extent than a single fascicle in the present study (~0.08 mm²). It is more difficult to reconcile the difference in mechanical properties between the anterior and posterior patellar tendon between the present study and that of Basso et al. (4).

Aside from age, gender, and technical aspects of testing, the possible size effect of the tissue on the mechanical properties (3) may make direct comparisons to previous data on patellar tendon difficult. Nevertheless, a modulus and strength of 307 and 44 MPa, respectively, have been reported in young subjects (20–44 yr) with a cross-sectional area of 76 mm² (16).
Others (20) have reported that a portion of the patellar tendon (15 mm²) had a strength and modulus of 65 and 660 MPa, respectively, which is similar to previous reports (6). Atkinson et al. (3) recently reported that the patellar tendon (17–52 yr) with a cross-sectional area of 20 mm² had a modulus of 200 MPa, whereas tendon specimens with a cross-sectional area of 1 mm² had a modulus of ~800 MPa (Fig. 4 from Ref. 3). The latter findings and other data (7) are well in agreement with the data of the present study. Therefore, in addition to carefully controlling for the size and or hierarchical level of the tendon, the present data suggest that the region of the patellar tendon may markedly influence the material properties. In the horse, it has been shown that region-specific differences exist with respect to collagen fibril diameter (29), and recently it was also shown that there appears to be a site-specific loss of larger size collagen fibrils in the core of ruptured human Achilles tendons (25). The present findings extend these previous observations of region-specific differences in structural components to include differences in mechanical properties. In the horse, it has been shown that region-specific differences exist with respect to collagen fibril diameter (29), and recently it was also shown that there appears to be a site-specific loss of larger size collagen fibrils in the core of ruptured human Achilles tendons (25). The present findings extend these previous observations of region-specific differences in structural components to include differences in mechanical properties. It remains to be established whether these region-specific differences may be attributed to factors such as fibril size and density (26, 27), cross links (8, 35), fibril length (30), and components of the extracellular matrix (21, 33).

The etiology of patellar tendinopathy remains unknown. It was recently suggested that the posterior portion of the tendon may be stress shielded (2). Others (4) have questioned tensile strain as an important pathogenic factor. The results of the present data on young, healthy men suggest that the fascicles of the anterior portion of the tendon have adapted to a functional demand to withstand far greater stress than those of the posterior portion of the tendon. To what extent these region-specific differences contribute to patellar tendinopathy remains elusive. Also, it remains to be established whether quadriceps loading in knee flexion may either decrease (2) or increase (4) posterior patella tendon tensile strain, and, moreover, to what extent training regimes with varying degrees of knee flexion may influence the region-specific material properties of the tendon.

Mechanical testing of tendon tissue is always associated with inherent limitations (see discussion on strain and preconditioning below). In the present study, one important source of variation is the determination of the fascicle cross-sectional area, which was obtained based on multiple measurements of the fascicle diameter. These measures yielded coefficients of variations of 5% for duplicate measures, and the variation appears to have been similar for anterior and posterior fascicles. Therefore, the magnitude of these potential sources of error are unlikely to account for the considerably greater yield stress (79%) or peak stress (100%) of the anterior tendon fascicles compared with that of the posterior fascicles. It is also possible that the loading rate may influence the mechanical properties of tendon, which, in the present study, were relatively low to avoid resolution problems with the video recording (15 Hz). It has been shown that failure stress and strain increases with increasing loading rate (37, 42), but that stiffness appears to be largely rate insensitive (5, 15, 17, 37, 42). However, although the loading rate may have affected the magnitude of stress and strain values, but not modulus, it is unlikely that it would have influenced the observed differences.

Fig. 4. A: fascicle length for a rat tail fascicle (based on grip-grip changes) loaded to a stress equal to ~4 MPa eight consecutive times with a 1-min hiatus. Note the considerable leftward shift from the 1st to the 6th cycle. B: means ± SE. *Significantly different from the 8th cycle, P < 0.05. C: fascicle length for human patella tendon fascicles (based on grip-grip changes) loaded to a stress equal to ~3 MPa five consecutive times with a 1-min hiatus. Note the considerable leftward shift from the 1st to the 2nd cycle. B: means ± SE. *Significantly different from the 5th cycle, P < 0.05.
in mechanical properties between the anterior and posterior human patellar fascicles.

To develop and assess the mechanical testing device and procedures, we chose readily available rat tail tendon (from one animal) with its easily dissected individual strands of collagen fascicles. The average peak stress obtained in the present study (∼13 MPa) is lower than previously reported (∼20 MPa) for collagen fascicles from rabbit patellar tendons (39, 40); however, the tangent modulus (725 MPa) compares well with that reported by others (800 MPa) (32). Because we chose to report strain at yield stress, i.e., before microfailure, the strain in the present study was lower than that reported by Dressler et al. (10) and C. Wu et al. (38). It is well accepted that the loading history will affect the mechanical properties of collagen tissues (14, 32, 36). However, despite the general acceptance of the necessity of such testing procedure, there is little or no information as to the number of cycles or magnitude required to obtain reproducible data. The present data confirm that a substantial rightward shift occurs in isolated rat collagen fascicles with repeated cycles and, moreover, that, under the present conditions, preconditioning beyond five cycles yielded constant lengths at force onset (see Fig. 4, A and B), which was eliminated from the reported strain.

It is well accepted that the loading history will affect the tendon properties with a rightward shift of the stress-strain curve (14, 32, 36). This rightward shift is particularly noticeable with the initial loading cycles, and it is, therefore, required to obtain reproducible data (14, 32, 36). However, despite the general acceptance of the necessity of such testing procedure, there is little or no information as to the number of cycles or magnitude required to obtain reproducible data. The present data confirm that a substantial rightward shift occurs in isolated rat collagen fascicles with repeated cycles and, moreover, that, under the present conditions, preconditioning beyond five cycles yielded constant lengths at force onset (see Fig. 4, A and B). Parenthetically, pilot trials indicated that a longer time interval (10 min) between cycles, which allowed the tissue to “recover,” yielded greater variability and, therefore, appeared to abate the ability to achieve reproducible data. Based on the results from the rat tail fascicles, we chose to perform five preconditioning cycles for the human tissue; however, statistical analysis proved that reproducible data, and, therefore, a “steady state,” were achieved already after the first cycle (see Fig. 4, C and D). Furthermore, these findings demonstrate that similar loading history may influence different types of collagen fascicles differently.

Table 1. The calculation of strain based on grip-to-grip deformation and tendon midsubstance deformation based on optical markers

<table>
<thead>
<tr>
<th>Reference</th>
<th>Tendon Tissue</th>
<th>Grip-Grip Strain, %</th>
<th>Midsubstance Strain, %</th>
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<tbody>
<tr>
<td>Butler et al. (6)</td>
<td>Human patellar tendon</td>
<td>30.2</td>
<td>12.0</td>
</tr>
<tr>
<td>Dressler et al. (10)</td>
<td>Rabbit patellar tendon</td>
<td>15.5</td>
<td>7.1</td>
</tr>
<tr>
<td>Devkota et al. (9)</td>
<td>Avian flexor tendon</td>
<td>16.4</td>
<td>12.2</td>
</tr>
<tr>
<td>Wu et al. (38)</td>
<td>Rat tibialis anterior tendon</td>
<td>15.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Present study</td>
<td>Rat tail fascicle</td>
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<td>2.6</td>
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<tr>
<td>Present study</td>
<td>Human patellar fascicle, anterior</td>
<td>12.4</td>
<td>6.8</td>
</tr>
<tr>
<td>Present study</td>
<td>Human patellar fascicle, posterior</td>
<td>13.0</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Note that, in all cases, grip-grip strain exceeds that of midsubstance strain.

Table 2. Strain and modulus at yield stress for anterior and posterior fascicles

<table>
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<th>Anterior Fascicle</th>
<th>Posterior Fascicle</th>
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<tbody>
<tr>
<td></td>
<td>Strain, %</td>
<td>Modulus, MPa</td>
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<tr>
<td>Midsubstance</td>
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<tr>
<td>Plate-plate</td>
<td>12.4±1.4*</td>
<td>510±76*</td>
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Values are means ± SD. Significantly different from midsubstance data obtained based on ink marks, *P < 0.05.
that tendon fascicles from the anterior portion of the human patellar tendon in young men displayed greater peak and yield stress and tangent modulus compared with the posterior portion of the tendon, indicating region-specific material properties. Whether the considerable region-specific difference in peak stress (100%) is a contributing factor to patella tendon injury remains unknown. Furthermore, preconditioning protocol yielded consistent data beyond five cycles in rat tail fascicles and, similarly, beyond one cycle in fascicles from human patellar tendon, indicating that loading history may influence different types of collagen fascicles differently.

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