

Regional Analysis of Mechanical Properties of the Human Patellar Tendon

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Introduction

Patellar tendon mechanical properties have been frequently studied due to the use of this particular tendon as a graft in ACL reconstruction, as well as its susceptibility to injury in athletes. Several biochemical and biomechanical investigations¹⁻⁶ have provided tissue and molecular level support clinical reports of proximal tendon injury susceptibility. Haraldsson et al. reported that the peak and yield stress of tendon fascicles from the anterior aspect of the human patellar tendon are greater than those of the posterior portion.⁵ Lavagnino et al, utilizing a combined experimental and computational approach, showed that the posterior-proximal tendon experiences higher mechanical strain compared to other regions of the tendon during loading, especially in activities with repetitive knee flexions and extensions.⁶ To our knowledge, however, there are no experimental studies which have determined the extent to which patellar tendon properties vary along its length, from patellar to tibial insertion points. Therefore, the goals of the present investigation were to compare mechanical properties of the proximal, central, and distal human patellar tendon, and to determine whether these properties differ within each specified region.

Methods

Four patellar tendons (three male, one female, ages 41, 42, 51 & 65 yrs) were procured within 48 h post-mortem from the Gift of Hope Organ Donor Network (Elmhurst, IL, USA). Following tendon harvest, the knees joints were examined and cartilage assessed using a modified Collins scale. Each tendon was sharply released from its proximal and distal bony insertions and subsequently divided longitudinally into lateral, central, and medial thirds. The medial third (~10mm in width) was further divided into three transverse portions creating a patellar region, central region, and tibial region and individually frozen at -20° C in PBS with protease inhibitors. On the day of testing, tendon regions were thawed and further divided into four longitudinal portions of approximately equal width (1 mm) using a custom sectioning device.

For each specimen, five measurements of width and thickness were taken along the tissue length using a precision caliper and laser displacement sensor (Keyence LK-G82, Woodcliff Lake, NJ, USA), respectively. Cross-sectional area was calculated as the product of mean width and thickness.

Mechanical Testing: Tensile testing was conducted using a materials testing system (MTS Insight 5, Eden Prairie, MN, USA). Each specimen was secured within custom designed plates by gripping across the anatomic (medial-lateral) width of the tendon; therefore, during testing the specimen (anterior-posterior) thickness served as the sample width with respect to the tissue grip faces. This technique was implemented in order to minimize the likelihood of tissue slippage and shearing near the grips during testing. A consistent grip-to-grip length of 10 mm was tested. A 44N load transducer was attached in series between the upper tissue grip and test actuator. Specimens were preloaded to a force level corresponding to 0.05 MPa tensile stress in order to establish the initial gauge length; this was followed by preconditioning between 0.05 MPa and 0.25 MPa at a rate of 0.1 N/s for 15 cycles. Specimens were then loaded to failure at a rate of 0.1 mm/s. Throughout all testing the tissue was kept moist with saline. The failure test was recorded using a 1 megapixel digital video camera and Digital Motion Analysis Software (Spica Technology Corporation, Maui, HI, USA). Time, force, actuator displacement, and video images were synchronously recorded at 48Hz.

Data Analyses: Stiffness was calculated as the steepest slope of the load-deformation curve spanning 40% of the data points collected between initiation of the load to failure test and the maximum load. Maximum stress was calculated by dividing the maximum load by the initial cross-sectional area. Grip-to-grip strain at failure was calculated by dividing the relative actuator displacement at maximum stress by the initial gauge length. There were a total of 16 specimens per region. Statistical comparisons between the patellar, central, and tibial regions were performed using a repeated measures 1-way ANOVA. The statistical significance level was set to $p < 0.05$. Minimum Variance Quadratic estimates were computed in SAS (PROC VARCOMP, SAS 9.2, Cary, NC, USA) for the variances of donor, of region nested within donor, and of slice nested within region.

Results

All specimens failed in their midsubstance, away from the test grips. No significant regional differences were found for cross-sectional area, failure strain, maximum stress, or stiffness (Table 1).

For cross-sectional area, failure strain and maximum stress, variability among donors was negligible. When considering cross-sectional area, 51% of the variance could be explained by anatomic region, while 49% of the variance could be explained by the within-region variability. For failure strain, 96% of the variance was due to subregions with the remaining 4% attributable to anatomic region. 45% of the variance in maximum stress could be explained by region and 55% due to the subregion. For stiffness, 12% of the variance was found to be based on the donor variability, 50% was due to region and 38% was attributable to subregion.

Anatomic Region	Cross-sectional Area (mm ²)	Stiffness (N/mm)	Strain at Failure	Maximum Stress (MPa)
Patellar	1.81 ± 0.70	6.9 ± 5.5	0.17 ± 0.06	5.8 ± 4.9
Central	1.66 ± 0.84	7.3 ± 5.2	0.16 ± 0.06	6.1 ± 4.6
Tibial	1.97 ± 1.18	8.0 ± 6.7	0.17 ± 0.07	6.1 ± 5.1

Table 1- Data from the 3 regions tested. No significant regional differences were found for any of the outcomes.

Discussion

In our prior analyses of adjacent tendon samples from the same donors presented here⁷ histopathologic abnormalities and proteoglycan composition were noted to vary along the tendon length. Interestingly, in the current study, no significant regional differences were found for any of the measured biomechanical properties. Together, these results imply higher functional (mechanical) demands upon, and possibly inferior reparative responses of, these specific tendon regions. Optical marker displacement data are presently being analyzed to supplement the biomechanical data presented herein. Biochemical characterization of these mechanically tested specimens is also ongoing.

In addition to comparing mechanical properties along the tendon length, the current study also examined specimens from multiple subregions within each of the proximal, central, and distal portions of the tendons. Despite a lack of significant differences *within* each of the three tendon regions, statistical analyses provided further insight into overall variance of the reported results. The variance was different for each parameter that was analyzed. The material properties of failure strain and maximum stress did not vary among donors, which could be explained by the fact that both of these properties are computed by normalizing to the tissue geometry. In contrast, stiffness – a structural property – showed variance attributable to donor, region and subregion variability.

The relatively high coefficients of variation of our results may reflect variations in fiber alignment as well as isolated fascicle disruption due to sectioning of tissues into thin test samples. There was also a disparity in size of the prepared specimens due to regional variation of the thickness of the patellar tendon; this variation was addressed by computing both structural and material properties for each specimen.

References

- 1) Samiric, T. et al. *Mat Biol.* 28(4):230-236. 2009.
- 2) Fu, S. C. et al. *Clin J Sport Med.* 17(2):129-134. 2007.
- 3) Scott, A. et al. *Scand J Med Sci Sports.* 18(4):427-435. 2008.
- 4) Khan, K. M. et al. *Radiology.* 200(3):821-827. 1996.
- 5) Haraldsson, B. T. et al. *J Appl Physiol.* 98: 1006-1012. 2005.
- 6) Lavagnino, M. et al. *Am J of Sports Med.* 36(11)2110-2118. 2008.
- 7) Christensen, J. et al. *Trans ORS.* 35:1068. 2010.

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