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# A comparison of the quasi-static mechanical and non-linear viscoelastic properties of the human semitendinosus and gracilis tendons

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ABSTRACT

*Background:* Over 50-% of anterior cruciate ligament reconstructions are performed using semitendinosus and gracilis tendon autografts. Despite their increased use, there remains little quantitative data on their mechanical behavior. Therefore, the objective of this study was to investigate the quasi-static mechanical and non-linear viscoelastic properties of human semitendinosus and gracilis tendons, as well as the variation of these properties along their length.

*Methods:* Specimens were subjected to a series of uniaxial tensile tests: 1-h static stress-relaxation test, 30 cycle cyclic stress-relaxation test and load to failure test. To describe the non-linear viscoelastic behavior, the quasi-linear viscoelastic theory was utilized to model data from the static stress-relaxation experiment.

*Findings:* The constants describing the viscoelastic behavior were similar between the proximal and distal halves of the gracilis tendon. The proximal half of the semitendinosus tendon, however, had a greater viscous response than its distal half, which was also significantly higher than the proximal gracilis tendon. In terms of the quasi-static mechanical properties, the properties were similar between the proximal and distal halves of the semitendinosus tendon. However, the distal gracilis tendon showed a significantly higher tangent modulus and ultimate stress compared to its proximal half, which was also significantly higher than the distal semitendinosus tendon.

*Interpretation:* The results of this study demonstrate differences between the semitendinosus and gracilis tendons in terms of their quasi-static mechanical and non-linear viscoelastic properties. These results are important for establishing surgical preconditioning protocols and graft selection.



## 1. Introduction

The anterior cruciate ligament (ACL) is the most frequently injured knee ligament during sports and work related activities, with tears occurring in approximately 150,000–200,000 people in the United States each year (Beaty, 1999). Because midsubstance tears fail to heal and the long-term results of conservative treatments are poor, most ACL ruptures in young and active people require surgical reconstruction using tissue grafts. In recent years, autografts consisting of the semitendinosus and/or gracilis tendons have become more popular being utilized in approximately one half of ACL reconstruction procedures (Forssblad et al., 2006). The primary reasons for their use include less reported donor site morbidity when compared to other autografts (Aglietti et al., 1993; Kartus et al., 2001; Pinczewski et al., 2002), as well as adequate initial stiffness and strength when compared to the native ACL (Pinczewski et al., 2002; Steiner et al., 1994; Hamner et al., 1999).

Graft constructs can consist of a single tendon, either the semitendinosus or gracilis tendon, looped over on itself (double-strand), or both tendons looped and combined to form a quadrupled semitendinosus and gracilis (QSTG) graft. A number of studies have investigated the structural properties of the doubled and quadrupled semitendinosus and gracilis tendon grafts in terms of load to failure and stress-relaxation experiments and found several variables influence these measurements including graft preparation, fixation to bone, temperature, and preconditioning protocols (Hoher et al., 2000; Nurmi et al., 2004; Ciccone et al., 2006; Steiner et al., 1994; Hamner et al., 1999). These studies have provided valuable information on the structural properties of graft constructs, which reflect the size, length, and quality of the tendons collectively.

The mechanical properties, on the other hand, describe soley the properties of the material or tissue quality and are independent of the size or amount of tissue. These data are important because they are intimately related to the composition and micro-architecture of a tissue. In addition, the data can be utilized within

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computational models to more accurately predict the behavior of constructs in response to clinically relevant loading conditions that cannot be simulated experimentally. Despite the importance of such data, relatively few studies have characterized the mechanical properties of individual semitendinosus and gracilis tendons, especially in terms of their viscoelastic behavior (Noyes et al., 1984; Butler et al., 1984; Donahue et al., 2001).

Previous studies have demonstrated that mechanical properties can vary significantly from tendon to tendon (Butler et al., 1984). These properties have also been shown to vary significantly along the length of tendons, with the tangent modulus generally increasing toward the distal attachment (Arruda et al., 2006). On the other hand, greater amounts of stress relaxation are observed near the muscle attachment (Eliasson et al., 2007). This variation is believed to be related to the function of tendons, i.e. to provide a transition between compliant muscle and stiff bone (Paxton and Baar, 2007). At the region near the bone (bone-tendon), the maximum tangent modulus of the tibialis anterior tendon was reported to be 2.1-fold higher than that of either the midsection (mid-tendon) or the tendon near the muscle (muscle–tendon) (Arruda et al., 2006). Such differences for a looped graft construct could result significant inhomogeneities of stress through the cross-section of an ACL graft.

Thus, a more complete description of the semitendinosus and gracilis tendons is not only important for graft selection and surgical decisions, but can also serve as inputs to finite element models for both ACL reconstruction and for modeling the mechanics of the lower extremity. From a basic science perspective, these data would provide insight into the potential disparity in mechanical behavior of two tendons from similar anatomical locations within the human body. More specifically, quantitative data on the quasi-static mechanical and non-linear viscoelastic properties between tendons and along their length is important to further understand structure function relationships of these tissues.

Thus, this study had two objectives. The first was to measure and compare the quasi-static mechanical and non-linear viscoelastic properties of human semitendinosus and gracilis tendons, while the second was to compare the properties of their respective proximal and distal halves. Since a larger percentage of the semitendinosus tendon's length resides in the musculotendinous junction, which is known to have less compact fibers that deviate from the longitudinal direction of the tendon (Paxton and Baar, 2007), we hypothesized that its proximal half (i.e. towards the musculotendinous junction) would demonstrate inferior mechanical properties and an increased viscous response compared to its distal half and to the corresponding proximal half of the gracilis tendon. Conversely, since a smaller percentage of the gracilis tendon's length resides in the musculotendinous junction, we further hypothesized that its mechanical behavior would be more homogenous throughout its length, with the distal portions of both tendons behaving similarly.

To test these hypotheses, the quasi-linear viscoelastic (QLV) theory was used to curve-fit the experimental data from stress-relaxation tests to obtain the five constants describing the instantaneous elastic response and reduced relaxation function ($A$, $B$, $C$, $\tau_1$, and $\tau_2$). These constants were utilized to predict the experimental peak stresses of a separate cyclic stress-relaxation experiment. The constants were then utilized for comparisons between the proximal and distal halves of the semitendinosus and gracilis tendons. Stress–strain curves were obtained from load to failure tests and utilized for comparisons of the quasi-static mechanical properties of the tissue samples. Parameters describing these properties were tangent modulus, ultimate stress, ultimate strain and strain energy density.

## 2. Methods

### 2.1. Experimental

Ten independent fresh-frozen, intact human cadaveric knee specimens were used in this study (mean 56, SD 8 years). The knee specimens were thawed at room temperature overnight before dissection. The semitendinosus and gracilis tendons were harvested from the tibial insertion site of the knees using a closed tendon stripper (Wolf Instruments, Knittlingen, Germany) and examined to ensure that there were no visible signs of damage. The tendons were then wrapped in saline-soaked gauze, placed into an airtight plastic bag and kept frozen at −20 °C until the day of testing *(*4–6 *months later)*, (Moon et al., 2006). Before testing, the tendons were allowed to thaw at room temperature and cleaned to remove the muscle and fatty tissues. The most distal 2 cm of the tendon (bony attachment) was removed and the proximal 18 cm of the tendon was taken for testing. Any remaining tissue towards the proximal end (muscle attachment) of the tendon was discarded. The entire 18 cm portion of the tendon was cut into two 9 cm long halves, which were referred to as the proximal and distal half of the tendon (Fig. 1).

The initial cross-sectional area of each tendon half was measured with a laser micrometer system (accurate to 0.1 mm$^2$) at three locations, i.e., distally, mid, and proximally along the longitudinal axis (Lee and Woo, 1988). Each half was then placed in a custom guide (width of the narrow portion was 3 mm) and cut into a dog-bone shape with an aspect ratio of approximately 10. The length of the narrow portion (30 mm) of the dog-bone was placed at the middle third along the length of each tendon half. A second series of cross-sectional area measurements of the dog-bone shaped tendon were taken at three locations along the axis of the narrow portion of each tendon half. The three measurements were averaged to serve as the cross-sectional area of the tendon half for Lagrangian stress calculations. Following cross-sectional area measurement, two round reflective markers about 20 mm apart along the long axis of the tendon were glued on the narrow portion of each tendon half for strain measurement. The motion of these reflective markers was recorded during testing using a video analysis system (Motion Analysis™ VP320, Willamette Valley, Oregon, USA). Prior tests revealed that the errors in the accuracy of strain measurement with this system are less than 0.2% (Smutz et al., 1996).

Each end of the tendon halves was clamped with a set of customized soft-tissue clamps with a thin piece of gauze placed on

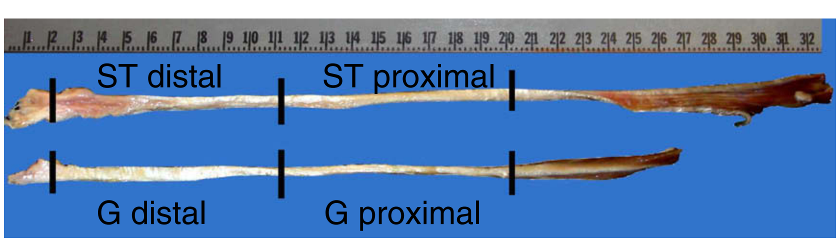


**Fig. 1.** A diagram defining the location of the proximal and distal halves of ST and G tendons at dissection (the major unit of the scale is cm).