Viscoelastic properties of six regions of the human patellar tendon

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INTRODUCTION: Anteroposterior differences in fascicle failure mechanics and collagen cross-links [1] have been attributed to the regional differences in *in vivo* human patellar tendon behaviour [2]. However, most *in vivo* tasks involve cyclic loading at stresses and strains below yield and failure points and thus potential differences in viscoelastic properties (i.e., time-dependent mechanical behaviour) would be more applicable for any potential regional differences in tendon mechanics. Regional viscoelastic properties may also be pertinent for the propensity of partial thickness tears posteriorly (resulting from tendinopathy) [3] and has relevance for tendon harvesting for anterior cruciate ligament reconstruction. However, no study to date has characterized viscoelastic properties of multiple regions of the human patellar tendon. Therefore, we aimed to fill this knowledge gap by performing stress relaxation and sinusoidal experiments on samples obtained from six different regions of cadaveric patellar tendons.

METHODS: Ethical approval was granted by the Research Ethics Committee of the Northern Savo Hospital District. Patellar tendons were harvested from eight thawed fresh-frozen cadavers (five female; mean age = 65±8 yr; mean height = 172±15 cm; mean mass = 83±23 kg) and frozen at -20°C for ~7 months. After thawing, external non-tendinous tissue was removed and the tendon was carefully divided into six regions: first, the tendon was cut into three mediolateral pieces, and then each mediolateral piece was subsequently divided at its approximate center width into anterior and posterior parts. From each of the six pieces, dumbbell shaped samples [4] were cut from the approximate longitudinal center with a custom-made tool (Figure 1). Sample cross-sectional area was obtained from micro-CT images (SkyScan 1172, Bruker). Stress relaxation and sinusoidal tests were performed on each sample using a mechanical testing device (Mach-1 v500css, Biomomentum). After preconditioning, a stress relaxation test consisting of a single step (8% strain at 10%/s velocity) was performed. After 30 minutes of relaxation, sinusoidal tests were performed at 0.1, 0.5, 1.0, 2.0, and 5.0 Hz at 0.5% strain amplitude from the nominal 8% strain. Twenty sinusoidal cycles were performed for a given frequency. Samples were immersed in phosphate-buffered solution for the entirety of mechanical testing, and the tests were performed at room temperature. The peak to equilibrium stress ratio was calculated from the stress relaxation data by dividing the peak stress by the equilibrium stress. Sinusoidal data were analyzed by fitting a sinusoidal function to stress and strain data at each frequency [4]: $z = A\sin(2\pi ft + \varphi) + z_o$, where z is the stress or strain value, A is the sinusoidal amplitude, f is the sinusoidal frequency, t is the time, φ is the phase angle, and z_0 is the equilibrium stress or strain. Phase difference was then calculated as stress phase angle minus strain phase angle, and dynamic modulus as the ratio of stress amplitude to strain amplitude. All data were analyzed as true stress and strain. Linear mixed models were performed in SPSS (v27, IBM) to assess the effects of region on peak to equilibrium stress ratio and the effects of regions and frequency on phase difference and dynamic modulus. Statistical significance was set at $p < 0.05$.

RESULTS: There were no effects of anteroposterior and mediolateral regions for peak to equilibrium stress ratio (all $p > 0.05$; Figure 2) or for phase difference or dynamic modulus (all $p > 0.05$; Figure 3). However, phase difference decreased significantly as a function of sinusoidal frequency ($p < 0.001$), although dynamic modulus did not ($p > 0.05$). Bonferroni post-hoc tests revealed phase difference was significantly different between all sinusoidal frequencies ($p < 0.038$; Figure 3).

DISCUSSION: Here, we have for the first time assessed the viscoelastic properties of six human patellar tendon regions via stress relaxation and sinusoidal tests. The results demonstrate no systematic anteroposterior or mediolateral regional differences in human patellar tendon viscoelasticity. As biochemical properties influence mechanical function [5], these results are consistent with previous work demonstrating no regional differences in biochemical composition at different mediolateral regions at the center of human patellar tendon [6]. Therefore, any regional differences in *in vivo* patellar tendon behaviour likely results from other factors, such as geometrical constraints and heterogeneous loading, rather than the composition or material properties of the tissue. However, the phase difference between stress and strain decreased with increasing sinusoidal frequency, demonstrating the patellar tendon behaves more elastically at higher strain rates, which may benefit joint control and movement economy in fast actions such as sprinting.

SIGNIFICANCE/CLINICAL RELEVANCE: Given the lack of regional differences in viscoelasticity, any heterogeneity in *in vivo* patellar tendon behaviour must result from factors other than tissue material properties, such as bone-tendon-bone geometry and heterogenous loading. These results also enhance the basic understanding of patellar tendon function with important implications for tendon injuries and tendon harvesting for reconstructive surgeries.

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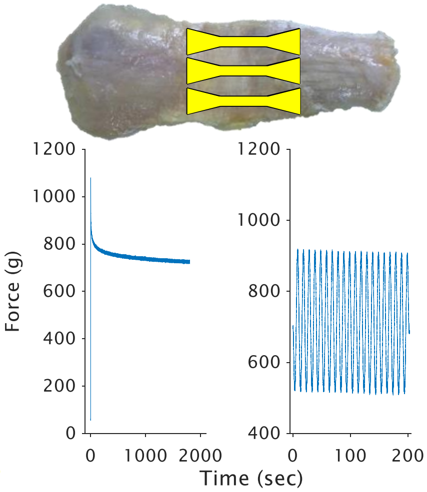

Figure 1. Example of mediolateral sample locations (top) and exemplary stress relaxation (bottom left) and sinusoidal 0.1Hz (bottom right) raw force-time curves.

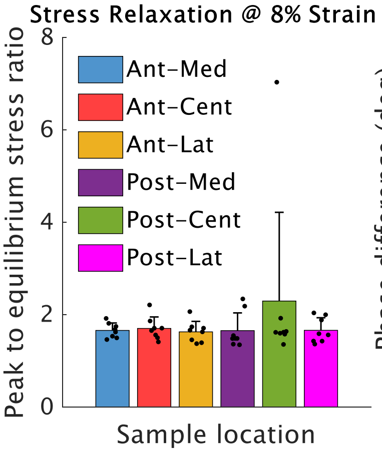

Figure 2. Means and standard deviations of the peak to equilibrium stress ratio. Individual datapoints are shown as filled black circles. *Ant*: anterior, *Cent*: central, *Lat*: lateral, *Med*: medial, *Post*: posterior.

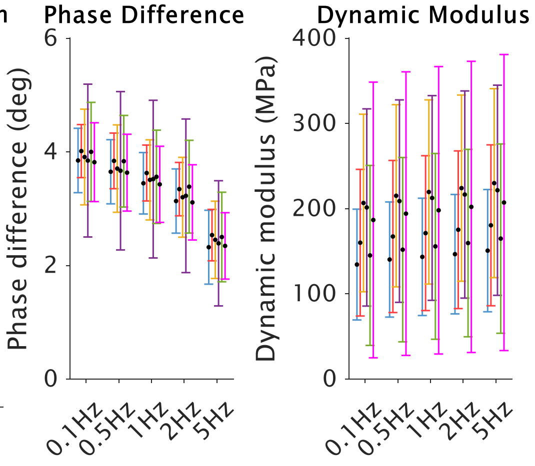

Figure 3. Means (filled black circles) and standard deviations of phase difference (left) and dynamic modulus (right) at five sinusoidal frequencies. The phase difference was significantly different between all frequencies ($p < 0.038$). See Figure 2 for legend.