Water Movement in Rabbit Achilles Tendon in Response to Repeated Static Tensile Loads Using One-Dimensional Magnetic Resonance Imaging

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Introduction: It is known that in structural tissues, such as tendons and ligaments, interstitial water plays a role in the mechanical behavior of the tissue. One common way to investigate the role of hydration is to modify the tissue hydration through drying or immersion in solutions of different osmolarity. It has long been known that the water content of structural tissue can change its material properties [1]. While poroelastic models have been formulated for materials loaded in compression, little work has been done on tissue loaded in tension. Tensile loading of tendons is known to both cause a loss of interstitial water [3] and to stiffen them. In this experiment we demonstrate water movement and mechanical creep responses caused by tensile loading, and contrast the time constants of these processes.

Methods: Achilles tendons (N=8) were harvested from the hindlimbs of young (3 kg) male New Zealand white rabbits. Tendons were removed in a near 100% humidity chamber. A length of #1 silk suture was tied to each end of the tendon. Tendons were stored in perfluoroalkylether (Krytox 107) oil to prevent dehydration. The RF coil was constructed from 16-gauge copper sheeting and formed into an oval-shaped solenoid of dimensions 3mm $\times$ 12 mm. The coil was mounted in a plastic chamber filled with Krytox. The apparatus was inserted in a vertical-bore 9.4T / 89 mm MR micro-imager (Varian INOVA) equipped with a 100 G/cm gradient insert from RRI (Billerica, MA). Tendon samples were oriented parallel to the static magnetic field. Tensile loads were applied using one end of the suture material connected to a DC servomotor operated in torque-control mode. Data acquisition was triggered by the controlling Labview program; load data were acquired from the motor. The linescan sequence was a slice-selective spin-echo pulse sequence without phase-encoding gradient. The excitation volume was defined by the intersection of two slice-selection planes 0.5 mm thick radially across the tendon and 2mm thick along the long axis of the tendon. This was done to cleanly separate signal from tendon rim and core regions. The linescan parameters were: 256 complex points, bandwidth = 80 kHz, signal averages = 4, TR = 2.0 s. Five linescan data sets, each acquired using a different TE, were used to calculate a 1-D M_0 map along the line. The echo times were TE = 4.0, 7.0, 16.0, 22.0, 25.0 ms. The M_0 map was calculated by fitting the data to the expression $M(\mathrm{TE}) = M_0 \exp(-\mathrm{TE}/T_2)$ on a voxel-by-voxel basis. The resulting M_0 maps were segmented into rim and core regions representing the edge and the center of the tendon. The pixels in each region were integrated, yielding a single value of M_0 for the rim (M_{0i}^{r}) and the core (M_{0i}^{c}), respectively. The integrated M_0 value for the entire tendon (M_{0i}^{tot}) was also calculated in order to determine if changes in M_0 were due solely to water redistribution. The experimental protocol consisted of two applications of 7.5N tensile loads (load = 42.67 min; unloaded =21.33 min, reloaded = 21.33 min, unloaded = 21.33 min). Proton density was measured continuously (every 40 sec). Separate creep tests were performed (N=7) to determine if the time course of the tendon creep was related to that of the water distribution.

Results and Discussion: Figure 1a,b shows the time courses of changes in M_0 for the rim and core regions, respectively. The data in Figs. 1a,b show that mean M_{0i}^{r} increases with a concomitant decrease in mean M_{0i}^{c}. This is the first direct evidence in a non-invasive experiment that water is redistributed from the core to the rim region upon loading. M_{0i}^{r} and M_{0i}^{c} were best fit using a monoexponential. The rate constant for M_{0i}^{r} were, for periods 1-4 respectively (in s^{-1}): $8.0 \pm 0.4 \times 10^{-4}$, $9 \pm 1 \times 10^{-4}$, $2.2 \pm 0.3 \times 10^{-3}$, $2.1 \pm 0.3 \times 10^{-3}$. M_{0i}^{c} data were fit well by a monoexponential in the initial loading period only; it was constant over time in all other periods. The rate constant for M_{0i}^{c} was, for period 1 (in s^{-1}): $1.9 \pm 0.2 \times 10^{-3}$. The results for mean M_{0i}^{tot} are plotted in Fig. 1c. While the time course of mean M_{0i}^{tot} follows the trends of mean M_{0i}^{r}, the amplitude of the percent changes are only ~30% of those of M_{0i}^{r}. These changes in M_{0i}^{tot} are consistent with the idea that water unbinds from the collagen matrix during loading, becoming NMR visible, and rebinds when the tendon is unloaded. The resulting rates from a monoexponential fit to the time course of the M_{0i}^{tot} data were statistically different from the rates of M_{0i}^{r} and M_{0i}^{c}. Displacement data (not shown) acquired from the motor controller results were best fit by a biexponential form and quantitatively different rate constants were measured in each period. These results are consistent with the model that water is redistributed from core to rim and that a smaller fraction of water becomes NMR-visible during loading. The processes of water redistribution, water becoming NMR-visible, and the mechanical behavior of the tendon are all separate behaviors.

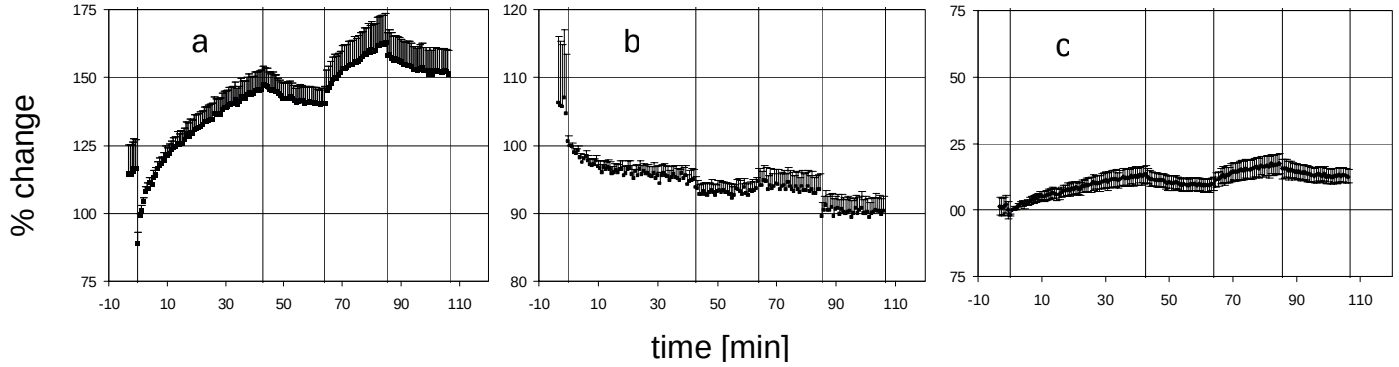

Fig. 1. Percent changes in M_{0i} for rabbit Achilles tendon rim region (a), core region (b), and total M_{0i} (c).

References: [1] Haut and Powlison J Orthop Res **8**(4): 532-40 1990. [2] Lanir et al Biorheology **25**(4): 591-603 1988 [3] Helmer et al. J. Biomech Eng., in press. **Acknowledgements:** This work was supported by NIH grant NS-10783.