A novel methodology for non-invasive and in vivo characterization of soft tissue mechanical properties using phase contrast MRI and MR-compatible dynamometer

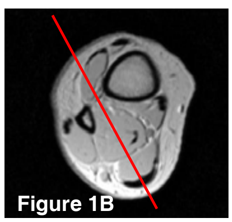
D. Shin[1], S. Ahn[1], J. Hodgson[2], R. Edgerton[1,2], and S. Sinha[3]

[1]Biomedical Engineering, University of California, Los Angeles, CA, United States, [2]Physiological Sciences, University of California, Los Angeles, CA, United States, [3]Radiology, University of California, San Diego, CA, United States

Introduction: Uniaxial load-displacement relation is commonly used to determine the biomechanical and structural properties of biological tissues, factors which can have profound effects on the overall response of the musculoskeletal system. We present a novel non-invasive approach using velocity-encoded phase-contrast magnetic resonance imaging (PC-MRI) in conjunction with a custom-built dynamometer for characterizing mechanical properties of the human Achilles tendon in vivo.

Objective: 1) To assess the accuracy and repeatability of the proposed methodology of quantifying the load-displacement profile in a group of normal subjects 2) to demonstrate its applications in a clinical setting in terms of assessing muscle function both in normal and atrophied musculoskeletal systems.

Materials and Methods: For MRI, both legs were placed under a multi-channel, phased array torso coil with one leg placed in the fiberglass cast. The imaged slice was prescribed oblique sagittally in the lower leg such that it bisected the center axis of the Achilles tendon (Fig. 1B). This ensured tracking displacement in the midsection of the tendon. The subject-specific anatomical location was preserved between imaging sessions to minimize spatially dependant variability. Imaging was performed with a spoiled gradient echo 2D phase-contrast sequence using VENC: 10 cm/s in the superior inferior direction, TR/TE/FA: 13.3 ms/7.5 ms/20º, slice thickness: 3 mm, receiver bandwidth: 290 Hz/pixel, 3 views per segment, 2 averages, image matrix: 128 x 256, FOV: 160 mm x 320 mm in the retrospectively gated mode to acquire 22 phases during 86 isometric contraction cycles. Plantarflexor force was recorded during the repetitive isometric contractions using a pre-calibrated strain transducer located under the sole of the cast, synchronized with an audio cue. Its output was used to gate the PC cine acquisition and subsequently averaged and calibrated to estimate the Achilles tendon force. Post-processed displacement (green dot in Fig. 1A) and corresponding tendon force were overlaid to create a load-displacement profile for 4 healthy subjects, i.e. S1-S4 (age: 29.0 ± 4.5 years, body mass: 72.8 ± 8.0 kg, height: 176.4 ± 9.9 cm, mean ± S.D.) over 2 different days (T1, T2) with one day gap. Within each day, test was repeated twice (R1, R2). In all, there were 4 repetitions per subject, which were used to generate a second-order least-squares polynomial curve. The correlation coefficient was calculated to assess the goodness of fit of each repeat with respective to the polynomial curve (Fig. 2). The polynomial curves obtained from each subject were plotted together (Fig. 3). One separate subject (age: 19 years, body mass: 66.7 kg, height: 167.6 cm) underwent 4 weeks of unilateral lower limb suspension on the left leg. The load-displacement behavior of the subject's tendon was monitored before and immediately after limb suspension using the poly-fitted curves based on which tendon stiffness and transition point were calculated (Fig. 4). Tendon stiffness was defined as the instantaneous slope (first derivative) of the function at 75% of the maximum tendon force. For an objective measure of "transition point", i.e. the point where the force-length curve becomes linear, a line was drawn from the same point where the stiffness was calculated, whose x-intercept was designated as the transition point.



Results and Discussion: 1) The correlation coefficient of each repeat set in reference to the "average" curve ranged from 0.89-0.99, 0.98-0.99, 0.97-0.99, 0.88-0.99 for S1, S2, S3, and S4, respectively, demonstrating high within-day and day-to-day repeatability of the methodology. 2) The subject-specific load-displacement curves revealed individual differences in tendon properties. 3) Following 4-week limb suspension, changes both in the elastic region (114.796 N/mm to 97.634 N/mm) and the non-linear "toe region" of the load-displacement curve (1.939 mm to 2.280 mm) were observed, both of which have significant implications on the muscle function.

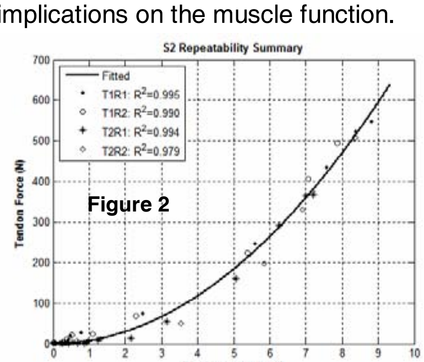


Figure 3

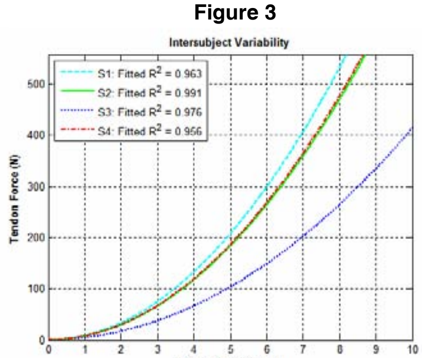
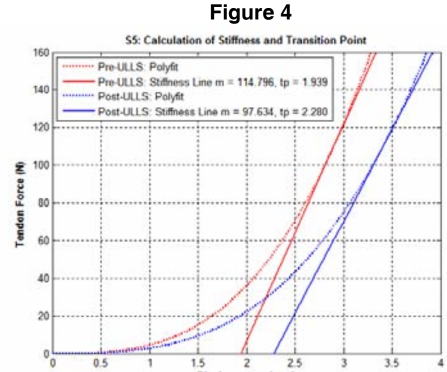


Figure 4



Conclusion: The method described herein of determining the elastic coefficients of human tendon in vivo from a non-linear description of the force-displacement curve, derived from a VE-PC MRI experiment, has necessary and sufficient repeatability and accuracy to demonstrate changes concomitant to advent of pathophysiological degeneration such as muscle atrophy.