Ultrasound Based Tendon Micromorphology Predicts Mechanical Characteristics of Degenerated Tendons

Yu-Jen Chang, MS¹, Gregory R. Bashford, PhD², Kornelia Kulig, PhD².
¹University of Southern California, Los Angeles, CA, USA, ²University of Nebraska - Lincoln, Lincoln, NE, USA.

Disclosures: Y. Chang: None. G.R. Bashford: None. K. Kulig: None.

Introduction: Tendon is a hierarchical fibrous connective tissue composed mainly of collagen fibers. The collagen fibers align in a bundle along the long axis of the tendon. The resulting tissue structure is visualized as a speckle pattern with notably parallel features on a sonogram. The mechanical characteristics of the tendon are related to the organization of the tissue architecture. Tendon mechanical characteristics in this study consist of both mechanical and material properties. Tendon’s mechanical properties relate to overall deformation resistance to of the whole tendon structure, whereas material properties represent the strength of each individual element within the tendon. When degenerated or injured, the collagen bundle organization is disrupted and the water content in the extracellular matrix (ECM) is increased. These changes in collagen bundle architecture affect the mechanical characteristics of the tendon. The ability to noninvasively quantify changes in mechanical characteristics on a sonogram would be useful to indicate the severity of tissue damage and the progression of tendon healing. Tendon architecture is manifested on a sonogram as quantifiable changes in the speckle structure of the image. The purpose of this study was to study the relationship between tendon micromorphology quantified from a sonogram and tendon mechanical characteristics measured in vivo in individuals with and without focal changes in tendon thickness indicating degeneration.

Methods: Subjects
Nineteen individuals (nine with unilateral Achilles tendinosis) participated in this study.

Micromorphology analysis of tendon images on ultrasound
Longitudinal ultrasound images were taken from the mid-portion of bilateral Achilles tendons. For tendon micromorphology analysis, regions of interest (ROIs) were selected and analyzed using a custom image analysis program written in MATLAB. Multiple kernels (32x32 pixels in dimension, corresponding to 4 mm²) were defined within each ROI. A two-dimensional fast Fourier transform (FFT) was performed within each kernel in order to perform spatial frequency analysis. In this study, the peak spatial frequency (PSF), which is the spatial frequency with the largest power in the image, was extracted. The PSF has been shown to correlate to the collagen bundle organization within the ROI.

Tendon mechanical properties measurement
Subjects lay prone on a HUMAC Norm isokinetic dynamometer with their testing foot tightly strapped to the foot plate. The ultrasound transducer was placed at the medial gastrocnemius muscle-tendon aponeurosis. Reflective markers were attached to the ultrasound transducer and bony landmarks to track the displacement of the ultrasound transducer and the distal attachment of the Achilles tendon. The subject was then asked to perform a maximal voluntary isometric plantarflexion contraction (MVIC) on the dynamometer to serve as the target torque. The MVIC was followed by three ramped maximal
voluntary isometric plantarflexion contractions, each with five seconds ramp-up, two seconds hold at maximal, and five seconds ramp-down. The subjects were asked to control the cursors on the dynamometer screen by plantarflexing their ankle, so that the predetermined torque curve fell in between the cursors. The position data of the reflective markers were captured using a 3-D motion analysis system with three cameras at 150 Hz. The torque was recorded synchronously with the positions of the reflective markers and the EMG signal by the Qualisys motion analysis system at a sampling frequency of 1,500 Hz. Ultrasound images taken during contractions were synchronized with the torque signal from the dynamometer and recorded at 30 frames/second with a custom LabVIEW program.

Variables for tendon moment arm length determination
The moment arm of the Achilles tendon was measured using the tendon travel method by slowly and passively moving the ankle joint from five degrees of dorsiflexion to five degrees of plantarflexion. The moment arm of the tendon was calculated using the following equation:
\[ MA = \frac{dL}{d\phi}, \]
where \( MA \) is the moment arm, \( dL \) is the displacement of the distal attachment of the tendon, and \( d\phi \) is the angular displacement of the joint, which was 10 degrees in this study.

Tendon force calculation
To calculate the tendon force, first, the torque contributed from the co-contraction of the tibialis anterior (TA) muscle was subtracted from the joint torque measured using a dynamometer. After accounting for the torque from the TA, the following equation was applied:
\[ ATF = \frac{TQ}{MA}, \]
where \( ATF \) denotes Achilles tendon force, \( TQ \) is the torque after accounting for TA torque, and \( MA \) is the moment arm calculated as described above.

Tendon elongation
The elongation of the tendon was calculated as a composite result from kinematics captured by the motion capture system, and the aponeurosis displacement from the ultrasound image. The displacement of the distal attachment of the Achilles tendon was presented as the heel marker displacement. The displacement of the aponeurosis was a combination of 1) aponeurosis displacement measured on the ultrasound images, and 2) the displacement of the ultrasound transducer calculated from the motion capture system. The overall tendon elongation was determined as the summation of the displacements of aponeurosis and reflective marker at the calcaneus.

The stiffness of the tendon during isometric contraction was determined by plotting the tendon force against tendon elongation. The stiffness was defined as the slope of the linear region of the curve. The elastic modulus was also calculated as a measure of material properties. Stress of tendon was calculated by normalizing tendon force to its cross-sectional area (CSA); and strain was calculated by normalizing tendon elongation to its resting length. The elastic modulus was defined as the slope of the linear region of the stress-strain curve.

Results: The Peak Spatial Frequency and the stiffness of the Achilles tendons show a high positive correlation \((R^2=0.75)\) in degenerated tendons (Fig. 2b), but a low correlation \((R^2=0.31)\) in healthy control subjects (Fig. 2c). A similar but more prominent relationship \((R^2=0.8)\) was observed between the PSF and the elastic modulus of the degenerated Achilles tendon (Fig. 3).
Discussion: Micromorphology was highly correlated with mechanical properties and even higher with material properties in tendinotic, but not healthy, tendons. The less pronounced relationship between micromorphology and tendon mechanical characteristics in healthy subjects may be due to the homogeneity and tight distribution of intact collagen bundles in ECM in tendons of healthy individuals. Degenerated tendons, on the other hand, show thinner, disorganized collagen fibers and increased water content in the ECM. These characteristics are captured by frequency analysis on the tendon’s sonogram. The findings in this study are similar to those in an in-vitro study on healthy and degenerated equine tendons.

Significance: This is the first study that predicted the mechanical characteristics of degenerated human Achilles tendon using a non-invasive micromorphology analysis approach. These findings show potential to improve classification and severity of the degeneration, as well as the response of the tendon to intervention.

![Image 1](image1.png)

*Figure 1. Frequency analysis of Achilles tendon ultrasound image. (a) Original B-mode image with a representative kernel selected (white box). (b) Frequency spectrum of the selected kernel.*

![Image 2](image2.png)

*Figure 2. Achilles tendon Peak Spatial Frequency versus stiffness on both sides of (a) both tendinotic and healthy control subjects, (b) tendinotic subjects, and (c) healthy control subjects.*
Figure 3. Achilles tendon Peak Spatial Frequency versus elastic modulus on both sides of (a) both tendinotic and healthy control subjects, (b) tendinotic subjects, and (c) healthy control subjects.