

Patellar Tendon Morphology and Biomechanics Across the Adult Female Lifespan

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INTRODUCTION: Loss of function, decreased quality of life, and higher risk of musculoskeletal injuries are well-known effects of menopause. Because of the decrease in endogenous estrogen production in aging women, postmenopausal women face greater risks of tendinopathy, tendon rupture, and sarcopenia. Structural and functional changes in tendons and muscles contribute to physical impairment and a lower quality of life. Despite these well-established outcomes, few studies have examined how menopause influences tendon properties. Additionally, limited research has investigated how female tendons change during the menopause transition. In this study, we analyzed the biomechanics and morphology of the patellar tendon in women across the adult lifespan (ages 21-75). We hypothesized that tendon biomechanical and morphological properties would decline with age and that the rate of decline would increase after women reach perimenopause. As a secondary goal, we evaluated quadriceps muscle strength and size to examine how these properties change alongside the patellar tendon. We used both magnetic resonance imaging (MRI) and ultrasound-based strain tracking to assess these properties in living subjects. Additionally, we employed T2* mapping to measure fibril disorganization within the tissue.

METHODS: Thirty-three pre-menopausal (Age: 28.4±1.2, BMI: 23.4±0.6), eight perimenopausal (Age: 47.8±0.7, BMI: 29.1±2.4), and forty-one postmenopausal (Age: 64.0±0.8, BMI: 27.8±0.8) participated in the study. Since our goal is to evaluate tendon and muscle properties in aging women, only women were recruited for this study. This project was approved by the Purdue University IRB (#IRB-2024-27). Images were obtained using the Siemens MAGNETOM PRISMA 3T whole-body MRI system combined with a 15-channel Tx/Rx Knee Coil. T2-star* images were obtained in 4-mm axial slices (no gap) from the distal pole of the patella to the tibial tuberosity (TR: 16.7 ms, TE: 0.03, 2.3, 4.6, 6.9, 9.2, and 11.25 ms; Field of View: 160x160, Resolution: 256x256, Voxel Size: 0.5x0.5x4 mm, Flip Angle: 12°). Quadriceps muscle imaging was captured using the same Siemens machine. Fifty 8-mm slices (no gap) were obtained beginning at the tibial notch and continued proximally (TR: 900 ms, TE: 4.3 ms; Field of View: 480x480, Resolution: 512x512, Voxel Size: 0.94x0.94x8 mm, Flip Angle: 120°). Quadriceps muscle volume was determined by circumscribing the rectus femoris and vastus complexes every third slice along the muscle length (Horos v3.3.6, www.horosproject.org). Tendon cross-sectional area (CSA) and T2* relaxation time were assessed using a custom MATLAB (MATLAB R2024a, The MathWorks, Inc.) script after a 3D mask was created to define the patellar tendon (3D Slicer v5.6.2, www.slicer.org). Biomechanical tests were completed with the subject seated upright at a 90-degree angle at the hip and knee joint. The ankle was attached to a rigid cuff attached to a force transducer, while an ultrasound probe was placed on the patellar tendon. Subjects completed a 10-second ramp, gradually increasing force output, reaching maximum effort at 10 seconds. Strain analysis was performed using a custom MATLAB graphical interface and was combined with force to determine the stress-strain relationship. Young's modulus was calculated as the slope of the final 20% for the linear region of the stress-strain curve. A one-repetition maximum (1-RM) leg extension test was used to quantify the muscular strength of the quadriceps.

RESULTS: All analyses were performed using either simple linear regression or non-linear regression with a second-order polynomial. The selection of the fit was based on Pearson's correlation coefficient. An alpha level of 0.05 was used to determine statistical significance. Patellar tendon biomechanical stress ($r=0.53$, $p<0.05$) and strain ($r=0.43$, $p<0.05$) were best described by simple linear regression and showed significant differences. However, Young's modulus ($r=0.24$, $p>0.05$, Fig. 1) did not reach significance. Both mean CSA ($r=0.41$, $p<0.05$, Fig. 2) and T2* relaxation time ($r=0.50$, $p>0.05$, Fig. 3) were best fitted with second-order polynomial regression. The size of the patellar tendon increased from 20 to 40 years of age, then rose rapidly from 40 to 75 years. T2* showed the most fibril disorganization during the peri-menopausal age range (45-54), with a return to a more organized tendon structure in postmenopausal women. Both 1-RM strength ($r=0.42$, $p<0.05$) and quadriceps volume ($r=0.68$, $p<0.05$, Fig. 1) decreased with age and were best modeled with simple linear regressions.

DISCUSSION: Our data suggest a more rapid increase in patellar tendon size following perimenopause but a gradual decline in Young's modulus across the lifespan. Together, these findings indicate an increase in fibril disorganization as women age. Yet, our T2* results indicate peak fibril disorganization was found during perimenopause, with a return to a more organized tissue in postmenopause. As both quadriceps size and strength declined linearly across the lifespan, an increase in patellar tendon size may be a compensatory mechanism to reduce stress placed on the tendon during perimenopause.

SIGNIFICANCE/CLINICAL RELEVANCE: Our findings indicate a peak in molecular disorganization during the perimenopausal stage, followed by tissue reorganization after menopause. Further research is needed to understand the mechanisms behind the increased fibril disorganization during perimenopause and to develop clinical methods to improve tissue properties and prevent musculoskeletal decline during menopause. Better understanding will help create clinical strategies to enhance musculoskeletal health as women age and transition through menopause.

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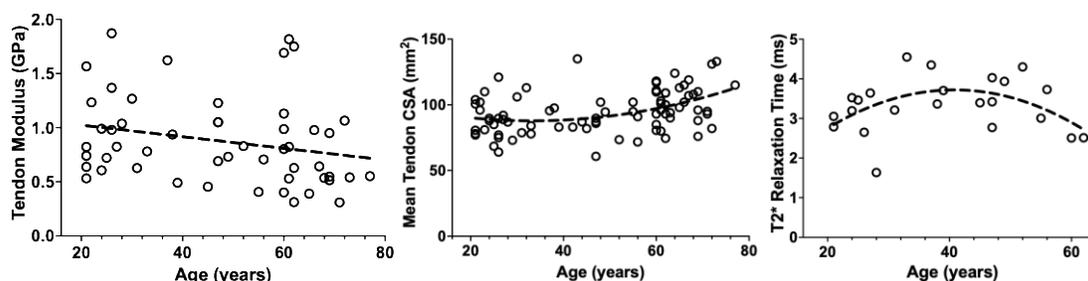


Figure 1

Figure 2

Figure 3