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STRUCTURAL AND MECHANICAL PROPERTIES OF THE HUMAN ACHILLES TENDON: SEX AND STRENGTH EFFECTS

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Abstract

Tendons are elastic structures that connect muscle to the skeletal system and transmit force relative to the amount of stretch they experience. The mechanical properties of human tendons are difficult to measure non-invasively, so generic values are often assumed in musculoskeletal models to represent all subjects. We aimed to determine the *in vivo* mechanical properties of the human Achilles tendon by calculating tendon stiffness and resting length in 10 male and 10 female trained cyclists. B-mode ultrasound coupled with motion capture was used to track the tendon lengths for the medial and lateral gastrocnemii concurrently with ankle torque measurements during ramped isometric contractions. Achilles tendon stiffness was calculated as the slope of the linear portion of the force-length curve, and this was extrapolated to zero force to yield the tendon resting length. Average Achilles tendon stiffness was $201.8 \pm 5.9 \text{ N mm}^{-1}$. There was no difference in Achilles tendon stiffness or maximum isometric force between males and females, however tendon stiffness varied between individuals. The resting lengths of the MG and LG tendon were $0.209 \pm 0.002 \text{ m}$ and $0.222 \pm 0.002 \text{ m}$ respectively, and regression models determined that shank length was the best predictor of resting tendon length. Our results indicate that Achilles tendon stiffness varies with muscle strength and not sex. The variability in Achilles tendon stiffness between subjects support the need for experimentally measured subject-specific tendon properties as input parameters to improve the accuracy of musculoskeletal models.

Keywords

Achilles tendon; ultrasound; stiffness; muscle model

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Conflict of interest statement

None.

INTRODUCTION

Hill-type muscle models and musculoskeletal simulations have broad application to biomechanical research and clinical investigations of musculoskeletal disorders. However, the accuracy of these simulations is sensitive to the values used for tendon stiffness and resting length (Gerus and Berton, 2012). Despite considerable variability in these tendon properties between individuals (Burgess et al, 2009; Kubo et al, 2003; Duclay et al, 2009), many studies use generic values for the tendon properties.

Previous studies have reported a wide range of stiffnesses for the gastrocnemius aspect of the Achilles tendon from 150 N mm^{-1} (Maganaris, 2002), 184.8 N mm^{-1} (Zhao et al, 2008) and 188 N mm^{-1} (Lichtwark and Wilson, 2005) to 390 N mm^{-1} (Muraoka et al, 2005) and 759 N mm^{-1} (Magnusson et al, 2003). This nearly 5-fold difference in the Achilles tendon stiffness is likely a result of differences in experimental methods employed in these studies and will have a dramatic effect on the outputs of musculoskeletal simulations. A few studies have investigated the effect of sex on tendon properties, but these have found varied results: females were reported to have lower stiffness for the Achilles tendon (Kubo et al, 2003), and the patellar tendon (Onambele et al, 2007); however, when muscle strength was taken into account it was shown that the stiffness of the Achilles tendon varied with the strength of the individual and not their sex (Muraoka et al. 2005).

The purpose of this study was to categorize the resting length and stiffness of the Achilles tendon for a range of male and female competitive cyclists. These data will inform future subject-specific musculoskeletal simulations of human movement. In this study we also test how tendon properties vary between the lateral and medial aspects of the Achilles tendon, and the extent to which the tendon properties vary with subject height, mass, sex and strength.

METHODS

10 male and 10 female trained cyclists (age 30.6 ± 7.3 years, mass 70.5 ± 10.5 kg and height 1.74 ± 0.07 m, mean $\pm$ SD) participated in the study and provided informed written consent as approved by the Office of Research Ethics at the University. The cyclists were tested after having undertaken a 90-minute cycling protocol for a different purpose. The cycling protocol was designed to be non-fatiguing, and prior to testing the Achilles tendon properties, there was a rest-period of minimum 15 minutes.

The force-length curves for the Achilles tendon were measured in a custom-made isometric frame (Rana and Wakeling, 2011). A strain gauge (Biovision, Wehrheim, Germany) measured force at the foot-plate and this was recorded using a 16-bit data-acquisition system (USB-6229; National Instruments, Austin, TX, USA). Achilles tendon force F_{AT} was calculated after accounting for the location of fulcrum and strain gauge relative to the ankle (Fig. 1).

Moment arms ma_{AT} for the MG and LG were calculated using subject-specific scaled models placed in the same joint configuration as our subjects (Arnold et al., 2010; OpenSim v3.2, Delp et al., 2007). Force-length curves were obtained for ramped contractions (subjects

increased force over a 3-second period) at ankle angles of -5 , 0 , 10 and 20° plantarflexion (knee angle fixed at 130°). Ultrasound images (60 mm linear-array B-mode ultrasound probe, Echoblaster, Telemed, Vilnius, Lithuania) were acquired for the muscle-tendon junction of the Achilles tendon with the medial- (MG) or lateral (LG) gastrocnemius muscles, and these were tested in a random order. The location of the muscle-tendon junction was manually digitized (ImageJ software, NIH, Maryland, USA) and mapped into the 3D laboratory coordinate system via the use of a calibrated 3-marker cluster rigidly mounted to the ultrasound probe (Prager et al., 1998; Rana and Wakeling, 2011). LED markers were also attached over the calcaneus and metatarsophalangeal joint and tracked using 3D motion capture (Certus Optotrak, NDI, Waterloo, Canada) (Fig. 1).

The Achilles tendon length was calculated as the Euclidean distance between the calcaneus and the muscle-tendon junction. Tracking the marker positions showed that in some cases the heel would pull off the foot-plate at the most plantarflexed condition, and for these cases a correction of 5 mm was added to the Achilles tendon length to accommodate the greater tendon curvature that can occur at pronounced plantarflexion levels (Stosic and Finni, 2011).

For each force-length curve, a least-squares linear line was fit to the linear portion of force-rise. This line was extrapolated to zero force to yield the resting-length l_0 , and the slope of the line was the tendon stiffness k . The maximum strain $\varepsilon_{\max}$ for each trial was taken as the maximum stretch of the tendon normalized to its resting length.

The effects of muscle, sex, ankle angle, height, mass and shank length (lateral tibial condyle to lateral malleolus) on the resting tendon length, maximum force, tendon stiffness and strain at maximum force were determined using ANOVA. Muscle, sex and ankle angle were treated as nominal variables, and height, mass and shank length as covariates. A subsequent ANOVA that additionally included $F_{\max}$ as a covariate tested whether variations in Achilles tendon stiffness were related to subject strength ($F_{\max}$). Factors were considered as significant at $p < 0.05$. Least-square linear regressions were performed between select variables and are reported with the standard errors for the coefficients. The coefficients of determination, r^2 , were calculated for these regressions (Minitab v16, Minitab Inc., State College, PA, USA).

RESULTS

There was substantial overlap in the range of heights, h , and masses, M_b , between the male and female subjects (Figs. 2A–B). There was no significant effect of sex on the outcome measures (Table 1), and instead the outcomes covaried with subject mass, height or shank length (Table 1).

Specifically, there was a significant difference in the Achilles tendon stiffness and the resting lengths between subjects (Fig. 3). There was no significant effect of ankle angle on Achilles tendon stiffness k . When pooled across all trials, the mean k was $201.8 \pm 5.9 \text{ N mm}^{-1}$ (Range: $142.6\text{--}307.7 \text{ N mm}^{-1}$). There was a significant effect of mass on k (Table 1) with a poor positive relation:

$$k=178.38 \pm 42.96+0.334 \pm 0.606M_b \quad [\text{N mm}^{-1}](r^2=0.01).$$

The maximum ankle torque, and thus the maximum Achilles tendon force $F_{\max}$, varied with ankle angle (Table 1), and was greatest at the neutral ankle angle of 0° (Fig. 2C). $F_{\max}$ increased with subject mass M_b in the following manner:

$$F_{\max}=296.0 \pm 837.1+32.2 \pm 11.7M_b \quad [\text{N}](r^2=0.17).$$

When $F_{\max}$ was included as a covariate, ANOVA showed a significant effect of $F_{\max}$ but not mass on the tendon stiffness, and k changed with $F_{\max}$ in the following manner:

$$k=125.1 \pm 26.7+0.0283 \pm 0.0096F_{\max} \quad [\text{N mm}^{-1}](r^2=0.19).$$

The resting length l_0 for the Achilles tendon was significantly different for the MG and LG muscles (Table 1), and the least-square means for l_0 were 0.209 ± 0.002 m for the MG and 0.222 ± 0.002 m for the LG, however no significant difference was found between MG and LG in k or maximum tendon strain $\epsilon_{\max}$. There was a significant effect of shank length l_{shank} on l_0 , with greater Achilles tendon resting lengths occurring in subjects with longer shank lengths:

$$I_{0,\text{MG}}=0.547 \pm 0.098I_{\text{shank}} - 0.0298 \pm 0.0428 \quad [\text{m}](r^2=0.33),$$

and

$$I_{0,\text{LG}}=0.735 \pm 0.069I_{\text{shank}} - 0.0987 \pm 0.0300 \quad [\text{m}](r^2=0.62).$$

The maximum Achilles tendon force normally occurred at the 0° ankle angle (Fig. 2), and the $\epsilon_{\max}$ reached at this ankle angle was $3.94 \pm 0.41\%$. Sometimes greater strains were measured at different ankle angles. When the greatest $\epsilon_{\max}$ was considered for each muscle and subject, the mean $\epsilon_{\max}$ was $4.99 \pm 0.80\%$. There was a small but significant effect of the subject height on $\epsilon_{\max}$ (Table 1) when considered for the whole data set, but this effect was not significant for those data at the 0° ankle angle and so this effect was not considered further.

DISCUSSION

The male and female subjects selected for this study had overlapping ranges for height and mass (Fig. 2A–B), and this allowed the effect of sex on Achilles tendon properties to be tested. Our results show no sex effect on any of the outcome measures (Table 1), and instead that l_0 , k and $\epsilon_{\max}$ varied with subject mass, height and shank length. The maximum Achilles tendon force achieved for the contractions varied with ankle angle, and this is to be expected due to the dependence of muscle force on length (Zajac, 1989), and the moment

arm on joint angle (Arnold et al, 2000). The maximum force achieved for each subject significantly covaried with subject mass, but not with height or sex (Table 1), and when $F_{\max}$ was included as a covariate, the variations in Achilles tendon stiffness were related to subject strength ($F_{\max}$), and not the height, mass or sex. These results do not support some of the previously reported sex effects on tendon stiffness (Kubo et al, 2003; Onambele et al, 2007), but they do support those by Muraoka and co-workers (2005). It should be noted that all of our subjects were trained cyclists, and the measured maximum force for male and female subjects was nearly identical ($p=0.936$). As Muraoka and co-workers (2005) noted, stiffness scales with strength and not sex. This is highlighted in our study as, unlike previous studies, there was no significant difference in the average strength, height or mass between the sexes.

The mean Achilles tendon stiffness from this study of $201.8 \pm 5.9 \text{ N mm}^{-1}$ is consistent with the range presented in current literature (Maganaris, 2002; Lichtwark and Wilson, 2005; Zhao et al, 2008). Although our subject population consisted of trained cyclists, we found variation in stiffness between subjects (Fig. 3), which is again consistent with previous literature (Burgess et al, 2009; Kubo et al, 2003; Duclay et al, 2009). Despite the relative homogeneity of our subject population the predictive relation between mass and tendon stiffness had poor predictive power, $r^2 = 0.01$, and this increased to only $r^2=0.19$ when $F_{\max}$ was used instead of mass for the regression: it is likely that there would be an even greater uncertainty in predicting tendon stiffness across different populations.

Possible limitations to this study are discussed below. The heel lifted away from the foot-plate for some of the subjects at the most plantarflexed condition. This resulted in the calcaneus marker moving closer to the muscle-tendon junction, but would have increased the curved length of the tendon (Stosic and Finni, 2011) and so tendon length was corrected in these cases. Nonetheless, there was no significant effect of ankle angle on the resting length of the Achilles tendon (Table 1). This result is to be expected because changes in ankle angle would passively lengthen the less stiff muscle fascicles rather than the tendon (De Deyne, 2001) and so l_0 should be independent of joint angle. This result provides confidence that results from the isometric frame were reliable. The maximum force reached during the contractions may be a slight underestimate due to the previous exercise that the subjects had undertaken, and the slightly flexed knee angle of 130° . Thus values of tendon stiffness and resting length should be unaffected by the underestimation of maximum force; however, the maximum strain reached by the tendon may be a slight underestimate. The maximum strains recorded here of 4.99 % are similar to Muramatsu et al. (2001) who report maximum strains of 5.1 % but less than those recorded for eccentric contractions 8.3 % such as one-legged hopping (Lichtwark and Wilson, 2005) where the forces and thus strains would have been higher. Finally, moment arms vary with contraction level in a non-linear fashion (Olszewski et al., 2015) and here we have only accounted for changes in moment arm as a result of joint angle, but not contraction level.

The findings from this study illustrate that generic values for tendon properties may not be appropriate, even for homogeneous populations, and supports the need for subject-specific tendon parameters as inputs to musculoskeletal models (Gerus and Berton, 2012).

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Fig. 1. Schematic of experimental setup with moment balancing equation used to calculate Achilles tendon force F_{AT} . Force F_G , was recorded using a strain gauge and converted to F_{AT} using the ratios of moment arms shown in the figure.

Fig. 2.
The overlapping ranges of male and female heights (A) and masses (B). The Achilles tendon force varied with ankle angle (C), with points showing mean $\pm$ standard deviation ($N=20$).

Fig. 3.

The linear portion of the Achilles tendon force-length curves during tendon stretch. Lines show males (blue) and females (red), with measurements from the muscle-tendon junction of the MG (dashed) and LG (solid). Lines extend to the maximum force achieved by each subject, and have the mean stiffness calculated from all four ankle angles. The intersection of each line with the x -axis shows the resting length l_0 , and the slope of each line gives the tendon stiffness k .

Table 1

Subject-specific parameters that affect the Achilles tendon properties. p-values from the ANOVAs are shown where significant and are shaded grey.

	Muscle	Height, h	Mass, M_b	Shank length, l_{shank}	Sex	Ankle angle
F_{max}	-	-	<0.001	-	-	<0.001
l_0	<0.001	-	-	0.014	-	-
k	-	-	0.039	-	-	-
ε_{max}	-	0.009	-	-	-	-