Elastic properties of human Achilles tendon are correlated to muscle strength

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Running head: tendon elastic properties and muscle strength

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Abstract

The purpose of this study was to investigate whether the mechanical properties of the Achilles tendon were correlated to muscle strength in the triceps surae in humans. Twenty-four men and twelve women exerted maximal voluntary isometric plantarflexion (MVIP) torque. The elongation (ΔX) and strain (ε) of the Achilles tendon, the proximal part of which is the composite of the gastrocnemius tendon and the soleus aponeurosis, at MVIP were determined from the displacement of the distal myotendinous junction of the medial gastrocnemius using ultrasonography. The Achilles tendon force at MVIP (F) was calculated from the MVIP torque and the Achilles tendon moment arm. There were no significant differences in either the F-ΔX or F-ε relationships between men and women. ΔX and ε were 9.8±2.6 mm and 5.3±1.6%, respectively, and were positively correlated to F (r=0.39, p<0.05; r=0.39, p<0.05), which meant that subjects with greater muscle strength could store more elastic energy in the tendon. The regression y-intercepts for the F-ΔX (p<0.01) and F-ε (p<0.05) relationship were significantly positive. These results might indicate that the Achilles tendon was stiffer in subjects with greater muscle strength, which may play a role in reducing the probability of tendon strain injuries. It was suggested that the Achilles tendon of subjects with greater muscle strength did not impair the potential for storing elastic energy in tendons and may be able to deliver the greater force supplied from a stronger muscle more efficiently. Furthermore, the difference in the Achilles tendon mechanical properties between men and women seemed to be correlated to the difference in muscle strength rather than gender.

Key words: tendon elongation, tendon strain, ultrasonography, stiffness
Introduction

The elasticity of the Achilles tendon provides an important mechanism: namely, the storage and release of elastic strain energy, which improves the economy and performance of motion (1, 2, 6, 25). Less tendon stiffness results in greater tendon elongation and greater elastic strain energy storage under a given extent of muscle force. Bobbert (2) showed in a simulation study that maximum jump height increased as the strain of the triceps surae tendon increased within a strain range between 1% and 15%. However, excess tendon elongation leads to a partial or complete tendon rupture (4), and the Achilles tendon is one of the most frequently injured tendons in the human body (11). Tendon stiffness therefore might increase with muscle strength, and thus reduce the probability of tendon strain injuries. Scott and Loeb (27) reported an in vitro animal experiment in which the stiffness of tendinous tissues (aponeuroses) was positively correlated to muscle strength. It must be noted here that excess tendon stiffness reduces tendon elongation upon muscle contraction and impairs the elastic strain energy storage and release in tendons. Scott and Loeb (27) reported that muscles with greater muscle strength had less tendon elongation at maximal contraction, which was disadvantageous for storing elastic strain energy in tendons (3). So far, little is known about the relationship between the mechanical properties of the Achilles tendon and muscle strength in humans.
The purpose of this study was therefore to investigate whether the mechanical properties of the Achilles tendon were correlated to muscle strength in the triceps in humans. We hypothesized 1) that the subjects with greater muscle strength had stiffer tendons and hence experienced the same or less elongation and strain at maximal voluntary contraction and 2) that there was no gender-related difference on these relationships because Kubo et al. (16) showed that both stiffness of the tendinous tissues of medial gastrocnemius and muscle strength were lower in women compared with men.

Methods

Twenty-four men and twelve women without histories of lower limb fractures or lower limb surgery (such as tendon or ligament repair) voluntarily participated as subjects. The anthropometric data of the subjects are shown in Table 1. The subjects were fully informed about the procedures and purpose of the study. Written consent was obtained from all. This study was approved by the ethical review board in The University of Tokyo.
ankle in the neutral position (the sole of the foot at right angles to the tibia axis), knee fully extended and the hip flexed to 70 to 80 deg. The axes of the ankle and the footplate were aligned as closely as possible. The right foot was tightly secured by two straps to the dynamometer’s footplate; the right thigh was also tightly secured by a strap to the dynamometer’s chair. To assess the fixation of the ankle during maximal voluntary isometric plantarflexion (MVIP), the ankle joint rotation angle during MVIP (θ) was measured using an electrogoniometer (model 45313, San-ei, Japan) with its ends attached to the tibia and the calcaneus (17). The angle data were A/D-converted (MacLab/8s, ADInstruments, Australia) and stored on a personal computer (model PowerbookG3/233, Apple, USA) at 200 Hz.

After a warm-up session with several repetitions of submaximal and maximal contractions, the subjects were asked to develop MVIP torque for 1s and to maintain it for 2s. The measurement was repeated twice for each subject with at least 2 min of rest between trials. The torque data were collected (with the acquisition system used for collecting the angle data) at 200 Hz. To estimate the Achilles tendon elongation at MVIP, the displacement of the distal myotendinous junction (Δx) of the medial gastrocnemius (MG) in the transition from rest to MVIP (Fig. 1) was measured using B-mode ultrasonography (SSD-2000, Aloka, Japan) (22). In the present study, the Achilles tendon was defined as the distance between the Achilles tendon...
insertion and the distal MG myotendinous junction. Thus, the proximal part of the Achilles tendon
is the composite of the gastrocnemius tendon and the soleus aponeurosis (8). The ultrasonography
data were collected at 30 Hz with a 7.5 MHz linear ultrasound probe attached to the dermal surface
by double-sided adhesive tape, which restrained the probe from sliding, over the medio-lateral
center of the MG. The ultrasonography data were A/D-converted (DVMC-DA2, Sony, Japan) and
stored on a personal computer (model iBook600, Apple, USA) for the measurement of \( \Delta x \) using
the public domain NIH Image program (developed at the U.S. National Institutes of Health and
available on the Internet at http://rsb.info.nih.gov/nih-image/). The ultrasonography, torque and
angle data were synchronized using a timer. Even in the isometric condition, joint rotation
occurred, resulting in the tendon displacement (29). To compensate for the influence of the ankle
joint rotation during MVIP on \( \Delta x \), the length change of the gastrocnemius muscle-tendon complex
due to the ankle joint rotation during MVIP was subtracted from \( \Delta x \) (19), with the result
abbreviated as \( \Delta X \) hereafter. The data regarding the length change of the gastrocnemius muscle-
tendon complex were derived from Grieve et al. (9), who reported the relationship between ankle
joint angle and the length change of the gastrocnemius muscle-tendon complex, which was
normalized with the lower leg length. Since there was no correlation (p>0.05) between \( \theta \) and some
parameters (MVIP torque, height, lower leg length, and body weight), there seems no systematic
bias for the relationships between \( F \) and \( \Delta X \), and between \( F \) and \( \varepsilon \). The positions of the Achilles
tendon insertion and the MG distal myotendinous junction at the neutral ankle joint position were detected using ultrasonography and were marked on the dermal surface. The distance between these two marks corresponds to the Achilles tendon length at rest (Lr) and was measured using a ruler. In addition, the position of the distal myotendinous junction of the soleus was detected using ultrasonography and was marked on the dermal surface. The distance between the Achilles tendon insertion and the distal myotendinous junction of the soleus corresponds to the free Achilles tendon length at rest (Lfr) and was measured using a ruler. The Achilles tendon strain at MVIP (ε) was calculated by dividing ΔX by Lr. The moment arm data were derived from Grieve et al. (9), who reported the Achilles tendon moment arm (MA) as a function of the lower leg length and ankle joint angle. Assuming that the influence of coactivation was zero, and the plantar flexion torque developed by plantarflexors except triceps surae was zero, the Achilles tendon force at MVIP (F) was calculated by dividing the MVIP torque by MA (19, 26) that was from the literature. Studies reported that the influence of coactivation on F was 2.6 to 5% (19, 26), which was practically negligible for the purpose of the present study. To date, it is impossible to accurately estimate the contribution of the triceps surae to the plantar flexors in terms of plantar flexion torque in vivo, because PCSA, moment arm length, and the force-length relationship were different for each plantarflexor in each subject. Although the plantar flexion torque developed by plantar flexors except the triceps surae is not zero and should be taken into consideration (7, 13,
24), the present study assumed that the plantar flexion torque developed by plantarflexors except the triceps surae was zero, as described in previous studies (19, 26), resulting in the overestimation of F. To estimate F accurately, MA should be measured in each subject at MVIP. Although we did not measure MA, we estimated MA while considering the influence of body size using previously reported data (9). In addition, we repeated statistical analyses using twenty sets of the data that included a random error of F within ±10%, and confirmed that the random error of F within ±10% did not affect the statistical significance of the results of the present study. Therefore, we considered that technical limitations of the method used in the present study did not change the conclusion of the study. We defined the Achilles tendon stiffness index (k) as the F divided by ΔX. This procedure for calculating stiffness was chosen because of the accuracy of the measured tendon elongation using ultrasonography, which is estimated to be about 1.0 mm. This value is not sufficient for measuring a short tendon elongation. Assuming that the tendon elongation in the transition from 50%MVIP to 100%MVIP is 4.2 mm (18), then an error of 1.0 mm in this value is about 24 %, which is much higher than the error in measuring the tendon elongation in the transition from rest to 100%MVIP (about 9% assuming an elongation of 11 mm at 100%MVIP; 18). In addition, Muramatsu et al. (22) reported that the strain of the Achilles tendon did not increase significantly with a torque increment above 30%MVIP. Therefore we decided to calculate the stiffness index using the data at rest and 100%MVIP.
Eighteen subjects (12 men and 6 women) of the present study participated in sporting activities (rugby, soccer, running, etc) more than twice per week for more than 10 months within the last year (active group). The regular training of this group did not include strength training (e.g. calf raises), the aim of which is to increase the muscle strength of the plantarflexors. The other eighteen subjects (12 men and 6 women) did not participate in regular sporting activities (sedentary group). Regular sporting activities might affect the mechanical properties of the tendinous tissues. However, the statistical results of the relationships between F and ΔX, F and ε, and body weight and k were the same for the active and sedentary group in the present study. Therefore, the influence of the physical activity level on the mechanical properties of the Achilles tendon and muscle strength was practically negligible for the purpose of the present study.

Values are presented as means (±SD). The differences in the F - ΔX relationship, and F - ε relationship between men and women were analyzed by a comparison of two regression slopes and y-intercepts. To test the significance of the relationships between F and ΔX, and between F and ε, the partial correlation coefficient for the parameters of F, ΔX, and body weight, and of F, ε, and body weight was calculated. To test the significance of the relationship between body weight and k, the partial correlation coefficient for the parameters of F, k, and body weight was calculated. To test the significance of the relationships between the Lft/Lr length ratio and ΔX, and between
the Lf/Lr length ratio and $\varepsilon$, Pearson’s correlation coefficient was calculated. When there was a significant relationship between parameters, a simple linear regression equation was calculated using the least square method. The level of significance was set to $p<0.05$. The reproducibility of $\Delta X$ was evaluated on the basis of the paired t-test, coefficient of variation (CV) and Pearson’s correlation coefficient (19).

**Results**

There was no difference in $\Delta X$ between the 1st trial (9.7 ± 2.7 mm) and the 2nd trial (10.0 ± 2.7 mm). There was a significant relationship between the two trials ($r=0.84$, $p<0.0001$). The mean CV value of $\Delta X$ between two trials was 10.1 (±6.6)%, which was within the range of previously reported data of 2.5% to 11.3% (19, 21, 22).

The mechanical properties of the Achilles tendon and the muscle strength in the triceps surae are shown in Table 2. $\Delta x$ and $\theta$ were 16.6 ± 4.1 mm and 8.8 ± 3.4˚; hence, $\Delta X$ was 9.8 ± 2.6 mm. There were no significant differences in either the regression slope or y-intercept of the $F - \Delta X$ relationship between men and women (Fig. 2A). There was a significant correlation between $F$ and $\Delta X$ ($r=0.39$, $p<0.05$) for the combined subjects. There were no significant differences in either the regression slope or y-intercept of the $F - \varepsilon$ relationship between men and women (Fig. 2B).
There was a significant correlation between F and $\varepsilon$ ($r=0.39$, $p<0.05$) for the combined subjects. The regression y-intercepts for the $F-\Delta X$ ($p<0.01$) and $F-\varepsilon$ ($p<0.05$) relationship were significantly positive. There was no significant correlation between F and $\Delta X$ ($r=0.19$), or between F and $\varepsilon$ ($r=-0.04$) for combined subjects. There was no significant correlation between body weight and $k$ for the combined subjects ($r=-0.13$) (Fig. 3). Lft and the Lft/Lr length ratio were 57 $\pm$ 16 mm and 0.30 $\pm$ 0.07, respectively. There was no significant correlation between the Lft/Lr length ratio and $\Delta X$ ($r=0.11$), or between the Lft/Lr length ratio and $\varepsilon$ ($r=0.11$).

**Discussion**

The main findings of this study were that the tendon force at MVIP positively correlated to both the elongation and strain of the Achilles tendon at MVIP, and that there was no gender-related difference on these relationships. Therefore, the hypothesis set out at the start of this study, which proposed that the subjects with greater muscle strength experienced the same or less elongation and strain at maximal voluntary contraction, was denied by the results of the present study. The hypothesis concerning a possible gender-related difference on the relationship between the mechanical properties of the Achilles tendon and muscle strength was supported (i.e. the difference was due to lower/greater muscle strength in women/men rather than a gender tie per se).
In the present study, $k$ was $390 \pm 90$ N/mm, which was consistent with the previously reported data of 237 to 304 N/mm obtained from in vivo Achilles tendons (18, 19, 26). The value of $\Delta X$ of $9.8 \pm 2.7$ mm in the present study was also consistent with the previously reported data of 10.2 to 11.1 mm (18, 19, 26).

In the present study, there were no significant differences in either the regression slope or the $y$-intercept of the $F - \Delta X$ and $F - \varepsilon$ relationships between men and women. Thus, we tested the significance of the correlation between $F$ and $\Delta X$ and between $F$ and $\varepsilon$ for the combined subjects.

So far, only one report (16) that has shown gender differences in the mechanical properties of human tendinous tissues. Kubo et al. (16) showed that the stiffness of the MG tendinous tissues was lower in women than in men, which was consistent with our results (Table 2), and concluded that there was a gender difference in tendon mechanical properties. However, Kubo et al. (16) did not examine the correlation between muscle strength and the tendon mechanical properties. Kubo et al. (16) showed that the strain of the MG tendinous was greater in women than in men, which was not consistent with our results (Table 2). This discrepancy between the results of the present and previous studies may be due to the difference in the method used for estimating tendon elongation, because Kubo et al. (16) did not consider the effect of the joint rotation during
isometric contraction that leads to a ~50% overestimation of tendon elongation (18, 19, 22, 26).

Our results suggest that the difference in the Achilles tendon mechanical properties between men and women was correlated to the difference in muscle strength, not to gender (Fig. 2).

In the present study, ΔX and ε were positively correlated to F, and the regression y-intercepts for the F-ΔX and F-ε relationship were significantly positive, which might indicate that the subjects with greater muscle strength had stiffer tendons. If all subjects have the same tendon stiffness index as the subject with weakest muscle strength has, most of subjects will experience greater tendon elongation and strain (Fig. 2). Since excess tendon elongation leads to a partial or complete tendon rupture (4), it is physiologically reasonable that subjects with greater muscle strength have stiffer tendons to reduce the probability of tendon strain injuries. On the other hand, body weight did not correlate to k (Fig. 3). Considering that normal healthy individuals walk approximately 7000–13000 steps per day (30), that the Achilles tendon load during locomotion is 1.4–9 kN (5, 14), and that the main load of locomotion is body weight, the Achilles tendon stiffness might increase with increasing body weight. However, Hansen et al. (10) showed that repetitive Achilles tendon loadings by means of running training for 9 months did not change the tendon stiffness of the triceps surae muscles. In addition, Kubo et al. (15) showed that the stiffness of human quadriceps tendinous tissues increased following isometric training for 3 months using
longer duration contractions (20 s) and did not change following isometric training using shorter duration contractions (1 s). Therefore, it may be speculated that the duration of Achilles tendon loadings during locomotion, which is a body weight load movement, is so short that repetitive loadings on the Achilles tendon through locomotion is an insufficient stimulus to stiffen the Achilles tendon.

In the present study, $F$ positively correlated to $\Delta X$ and $\varepsilon$ (Fig. 2). This result was not consistent with Scott and Loeb’s finding (27) from an in vitro animal (cat soleus muscle) experiment that the elongation of aponeuroses at maximum contraction significantly decreased and that of tendons tended to decrease depending on muscle strength. The tendinous tissues of cat soleus muscle were only twice as long as the muscle fascicles (28), and the tendinous tissues of the human triceps surae, which included the Achilles tendon and gastrocnemius aponeuroses, were seven times longer or more than the muscle fascicles (23). This difference in muscle architecture may reflect that the human Achilles tendon plays a more important role in the elastic strain energy storage and release in tendons during movements than do the tendinous tissues in cat soleus muscle. Achilles tendon strain values in the present study (2.1% to 9.3%) were within the strain range where the maximum jump height increased as the strain of the triceps surae increased (2). Therefore, the result that $F$ positively correlated to $\Delta X$ and $\varepsilon$ seems to be physiologically
reasonable. If subjects with greater muscle strength have excess tendon stiffness, the maximum tendon strain and maximum elastic energy storage in the tendons could be less than those in subjects with less muscle strength. The results of the present study, however, showed that the maximum tendon strain for subjects with greater muscle strength was greater than that for subjects with less muscle strength, and hence maximum elastic energy storage in tendons for subjects with greater muscle strength was greater than that for subjects with less muscle strength. It must be noted here that the result that $F$ positively correlated to $\Delta X$ and $\varepsilon$ might signify an increase in the probability of tendon rupture for subjects with greater muscle strength, since the safety factor for the human Achilles tendon was low (12). Further research should be done to clarify the relationship between the mechanical properties of the Achilles tendon and muscle strength in subjects with greater muscle strength than those in the present study (e.g. weight lifters).

Magnusson et al. (20) reported that the free Achilles tendon demonstrated greater strain compared with that of the aponeurotic part of the Achilles tendon. Therefore, assuming that there was no inter-individual difference in the strain ratio of the free Achilles tendon and the aponeurotic part of the Achilles tendon, the Lft/Lr length ratio might be positively correlated to $\Delta X$ and $\varepsilon$. In the present study, however, there was no significant correlation either between the Lft/Lr length ratio and $\Delta X$, or between the Lft/Lr length ratio and $\varepsilon$, which might be due to the relatively small
inter-individual difference in the Lf/Lr length ratio and/or to the inter-individual difference in the strain ratio of the free Achilles tendon and the aponeurotic part of the Achilles tendon.

In conclusion, there is a possibility that the stiffness of the Achilles tendon is positively correlated to the tendon force at maximal voluntary contraction. The stiffness of the Achilles tendon is not correlated to body weight. Achilles tendon elongation and strain at maximal voluntary contraction are positively correlated to the tendon force at maximal voluntary contraction. There is no gender-related difference on the relationship between the mechanical properties of the Achilles tendon and muscle strength (other than greater/lesser strength between men/women). It is suggested that the Achilles tendon of subjects with greater muscle strength does not impair the potential for storing elastic energy in tendons and may be able to deliver the greater force supplied by a stronger muscle more efficiently. Furthermore, it is noted that the difference in the Achilles tendon mechanical properties between men and women seems to be correlated to the difference in muscle strength, rather than gender.
Grants

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Figure legends

Figure 1

Sagittal plane ultrasound images over the distal myotendinous junction of the media gastrocnemius muscle for 1 subject. The myotendinous junction, indicated by white arrows, moves proximally in the transition from rest (top) to maximal voluntary isometric plantarflexion (bottom).

Figure 2

The relationships between the tendon force (F) in the triceps surae at maximal voluntary isometric plantarflexion, Achilles tendon elongation (ΔX), and Achilles tendon strain (ε). The thick, thin, and dotted thin lines are simple linear regression lines for combined subjects, men (closed circles), and women (open circles), respectively. The thick gray lines are simple linear regression lines for combined subjects assuming that all subjects have the same stiffness index as the subject with weakest muscle strength has. Regression equation of the relationships for combined subjects is:

\[ \Delta X = 1.6 \cdot 10^{-3} \cdot F + 3.6, \quad \varepsilon = 7.4 \cdot 10^{-4} \cdot F + 2.3 \]
Figure 3

The relationships between body weight and Achilles tendon stiffness index (k). Regression line is not shown since the relationship is found to be insignificant.
Tables

**Table 1** Anthropometric data of subjects

<table>
<thead>
<tr>
<th></th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Body weight (kg)</th>
<th>Lower leg length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>men (n=24)</td>
<td>27 ± 4</td>
<td>174 ± 7</td>
<td>71 ± 12</td>
<td>40 ± 2</td>
</tr>
<tr>
<td>women (n=12)</td>
<td>25 ± 5</td>
<td>161 ± 6</td>
<td>53 ± 6</td>
<td>37 ± 2</td>
</tr>
<tr>
<td>combined (n=36)</td>
<td>27 ± 4</td>
<td>170 ± 9</td>
<td>65 ± 13</td>
<td>39 ± 3</td>
</tr>
</tbody>
</table>

Values are means ± SD.
Table 2 Mechanical properties of the Achilles tendon

<table>
<thead>
<tr>
<th></th>
<th>TQ (Nm)</th>
<th>F (N)</th>
<th>Lr (mm)</th>
<th>ΔX (mm)</th>
<th>ε (%)</th>
<th>k (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>men (n=24)</td>
<td>197 ± 41</td>
<td>4229 ± 805</td>
<td>199 ± 33</td>
<td>10.8 ± 2.4</td>
<td>5.6 ± 1.7</td>
<td>406 ± 92</td>
</tr>
<tr>
<td>women (n=12)</td>
<td>124 ± 37</td>
<td>2856 ± 757</td>
<td>173 ± 15</td>
<td>8.0 ± 1.8</td>
<td>4.6 ± 1.1</td>
<td>357 ± 79</td>
</tr>
<tr>
<td>combined (n=36)</td>
<td>172 ± 52</td>
<td>3772 ± 1018</td>
<td>190 ± 30</td>
<td>9.8 ± 2.6</td>
<td>5.3 ± 1.6</td>
<td>390 ± 90</td>
</tr>
</tbody>
</table>

Figure 1

[Image of an ultrasound scan with arrows indicating proximal and distal directions and a scale of 10mm]
Figure 2

A) 

B)