MECHANICAL PROPERTIES OF ACHILLES TENDON IN YOUNG MALES AND FEMALES

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INTRODUCTION

The high stress in Achilles tendon occurs in daily life and sports. Ker et al. (1988) estimated the in vivo stresses imposed on various tendons and suggested that the peak stresses imposed on human Achilles tendon were above twice compared with those on other tendons. However, mechanical properties (failure strain, failure stress and Young’s modulus) of Achilles tendon were similar to other tendons (Wren et al., 2001). Therefore, Achilles tendon is one of the most frequently injured tendons in the human body (Jozsa and Kannus, 1997).

When tendons were subjected to cyclic stresses with a constant load at physiological frequencies, the number of cycles endured until tendon failure decreased as the load increased (Schechtman and Bader, 1997). Since major determinant of maximum tendon stress during slow concentric or static activities is muscle strength, Achilles tendon is expected to become stiff by qualitative and/or quantitative adaptation to avoid tendon injuries while muscle strength increases. It is noticed that the greater load beyond the muscle strength could be imposed on tendons during quick eccentric activities such as walking. The stresses that the normal healthy human Achilles tendon experiences most frequently in the human daily life occur during walking. Gidding et al. (2000) estimated that the peak force imposed on Achilles tendon during walking at 1.62 m/s was 3.9 body weights. In addition, Achilles tendon stored and released elastic energy during walking to reduce the energetic cost (Fukunaga et al., 2001). Therefore, a constant strain of Achilles tendon may be observed during walking irrespective of its mechanical properties.

The aim of this study is to investigate the relation between the mechanical properties of Achilles tendon and muscle strength. We hypothesized that 1) Achilles tendon became stiff while the muscle strength increased, and 2) a constant strain of Achilles tendon was observed during walking irrespective of its mechanical properties.

METHODS

Twenty-nine healthy males and twelve healthy females voluntarily participated in this study. The means (±SD) for age, height, mass and lower leg length were 26 (±4) yr, 169 (±8) cm, 64 (±13) kg and 39 (±3) cm respectively. The lower leg length was defined as the distance between the popliteal crease and the center of the lateral malleolus. The subjects were fully informed about the procedures to be used as well as the purpose of the study. Written informed consent was obtained from all subjects.

The cross-sectional area (CSA) of Achilles tendon (CSA_ac) and tendon strain in medial gastrocnemius (MG) during maximum voluntary isometric plantar flexion (MVC) were measured using ultrasonography. The MVC torque was also measured using a dynamometer.

The CSA_ac (Figure 1) was measured at 10% of the lower leg length proximal to the insertion of Achilles tendon, where the Achilles tendon ruptures occurred more frequently (Jozsa et al., 1989). The resting tendon length in MG (Lto) was measured at rest as the distance between the distal myotendinous junction in MG and the insertion of Achilles tendon at the ankle joint angle of 90˚ with the knee joint fully extended. The tendon elongation in MG during MVC was measured as the displacement of the distal myotendinous junction in MG (Figure 2). The ankle joint
rotation was measured using electrical goniometer and its effect on the displacement of the distal myotendinous junction in MG was corrected using the relation between muscle length change and ankle joint angle that is reported by Grieve et al. (1978). As a parameter that represents muscle strength, the tensile Achilles tendon force during MVC (\(F_{\text{max Ac}}\)) was calculated from the MVC torque and the estimated Achilles tendon moment arm using the data from Grieve et al. (1978) who reported the Achilles tendon moment arm as a function of the lower leg length.

The stress during MVC was defined as \(\sigma = F_{\text{max Ac}} / \text{CSA}_{\text{Ac}}\). The strain during MVC was defined as \(\varepsilon = d / L_0\), where \(d\) and \(L_0\) was the elongation and resting length of the tendon in medial gastrocnemius, respectively. Young’s modulus of Achilles tendon was defined as \(E = \sigma / \varepsilon\). Stiffness (\(k\)) in this study was defined as \(k = F_{\text{max Ac}} / \varepsilon\).

The maximal Achilles tendon strain during walking was estimated from stiffness obtained in this study and the reported value of maximal tensile force imposed on Achilles tendon during walking (Gidding et al., 2000; 3.9 body weights). Statistical significance was set at a level of \(p<0.05\).

RESULTS

Although stiffness significantly increased while Young’s modulus increased (\(r=0.862\), Figure 3), \(\text{CSA}_{\text{Ac}}\) was not correlated to stiffness (Figure 4). Although stiffness was positively correlated to \(F_{\text{max Ac}}\) (\(r=0.415\), Figure 5), the maximal strain during MVC and walking significantly decreased while stiffness increased (Figure 6, \(r=-0.523\); Figure 7, \(r=-0.717\)).

DISCUSSION

Main findings of this study were 1) Achilles tendon became stiff mainly by qualitative adaptation while muscle strength increased and 2) the maximal strain of Achilles tendon during MVC and walking decreased while Achilles tendon became stiff.

\(\text{CSA}_{\text{Ac}}\), maximal stress and strain during MVC, and Young’s modulus were within the reported values (Table 1).

The Young’s modulus in this study was calculated using the strain in the transition from rest to MVC. Since the stress-strain relation is curvilinear (Lewis and Shaw, 1997) and previously reported Young’s modulus values were obtained at the linear region of the stress-strain curve, the Young’s modulus obtained in this study might be underestimated.
increased (Figure 4). Therefore, it is suggested that the increase in stiffness is mainly due to qualitative changes. Studies reported that a long-term exercise resulted in the qualitative adaptation of tendons (Buchanan and Marsh, 2001; Kubo et al., 2000), but contrary result that quantitative adaptation occurred was also reported (Rosager et al., 2002). To clear the mechanism of adaptation in tendons, longitudinal studies may be needed.

Since stiffness increased while muscle strength increased (Figure 5), it is suggested that the adaptation in Achilles tendon occurred to avoid the increasing possibilities of tendon injuries with increasing muscle strength. It is noticed that long-term running exercise resulted in the increase in stiffness or CSA while muscle strength remain constant (Buchanan and Marsh, 2001; Kubo et al., 2000; Rosager et al., 2002). It could be speculated that the relation between stiffness and muscle strength was changed by long-term running exercise that imposed non-daily stresses on Achilles tendon.

In this study, we hypothesized that a constant strain of Achilles tendon was observed during walking irrespective of its mechanical properties to function as an energy store to reduce the energetic cost. However, strain both during walking and MVC decreased while stiffness increased (Fig. 6 and 7), which might result in the increase of energetic cost during motions. This results could suggested that the priority in tendon adaptation was not the reduction of energy cost during motion but the prevention of tendon injuries

REFERENCES


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Table 1: Mechanical properties of Achilles tendon (mean ± SD)

<table>
<thead>
<tr>
<th>Stiffness</th>
<th>Achilles tendon force</th>
<th>Achilles tendon CSA</th>
<th>Stress</th>
<th>Strain</th>
<th>Young’s modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>63 ± 20 kN</td>
<td>3184 ± 836 N</td>
<td>55 ± 10 mm²</td>
<td>58 ± 12 MPa</td>
<td>5 ± 2 %</td>
<td>1177 ± 370 MPa</td>
</tr>
</tbody>
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