Effects of Achilles Tendon Path Change on the Myotendinous Junction Movement of the Gastrocnemius Muscle

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The effects of the Achilles tendon path change due to muscle contraction on the displacement of the myotendinous junction were determined in the human in vivo. Seven male subjects, whose knees were extended and ankles flexed at a right angle, performed isometric plantar flexion while the Achilles tendon length within the predetermined area (from the point of the myotendinous junction at rest to the calcaneus) was estimated using a high-speed camera and ultrasound apparatus. The Achilles tendon length within the predetermined area decreased by ~1% at maximal voluntary contraction compared to the relaxed condition, which suggests that the Achilles tendon path change due to isometric contractions moves the myotendinous junction proximally by ~1%, at the most, of the Achilles tendon length. If we simply calculate the Achilles tendon strain based on the displacement of the myotendinous junction as in previous studies, we would therefore overestimate the strain by ~1%. This suggests that the tendon path change should be taken into account when tendon strain is calculated from myotendinous junction movements.

Keywords: achilles tendon, strain, path, human, in vivo

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1. Introduction

Since tendinous tissues (tendons and aponeuroses) connect muscle fibers to bones, their mechanical properties directly influence the behavior of the muscle-tendon unit. The elasticity of tendinous tissues influences the efficiency of exercise [Alexander (1984), Robert et al. (1997)] and the force-length and force-velocity characteristics of the muscle-tendon unit [Ichinose et al. (2000), Kawakami and Lieber (2000)]. Thus, many studies have focused on tendinous tissue elasticity using animals [Rack and Westbury (1984), Scott and Loeb (1995)] or human cadavers [Benedict (1968), Lewis and Shaw (1997)]. These studies have clarified the relationship between the force applied to the tendon and its elongation, but results might not be directly applicable to humans in vivo because of interspecies differences [Ker et al. (1988)] and/or the effects of sterilization or preservation of tissues [Smith et al. (1996)]. Recently, several studies have reported on the elasticity of human tendons [Maganaris and Paul

(2000a, b), Muramatsu et al. (2001)] and aponeuroses [Maganaris and Paul (2000a, b), Muramatsu et al. (2002a, b)] in vivo by using ultrasonography. In these studies on human tendons in vivo, tendon elongation was assumed equal to the displacement of the myotendinous junction during isometric contraction. As far as we know, this is the sole noninvasive approach to estimating tendon elongation or strain. However, this approach may be affected by tendon path change during muscle contraction. Therefore, information on the effects of the tendon path change is necessary. In the present study, we use the words "tendon path" to indicate the whole form of the tendon.

The present study aimed to clarify the effects of tendon path change due to muscle contraction on the displacement of the myotendinous junction and to discuss methods for estimating tendon strain.

2. Methods

2.1. Subjects

Subjects were seven healthy men (age 28 ± 3 yr, height 173 ± 7 cm, weight 71 ± 9 kg, means $\pm$ S.D.). Purposes and procedures were explained to subjects before obtaining their consent to participate in the study. The Tokyo University ethical committee approved this study.

2.2. Experimental Setup

An electric myometer (Myoret RZ-450; Asics, Tokyo, Japan) was used to fix the right ankle joint and to measure plantar flexion torque (**Fig.1-A**). Each subject lay prone on a bed, with the right foot firmly secured to the footplate of the myometer with straps. All tests in the present study were executed in this position. The center of rotation of the myometer was visually aligned with that of the ankle joint. The foot was fixed at the neutral anatomical position, where the sole of the foot was at 90° to the tibia (**Fig.1-A**). This ankle angle was defined as 90° . The left knee was kept flexed so that the right leg was in view of the camera. Using ultrasonic apparatus (SSD-2000, Aloka, Tokyo, Japan), we detected the most distal part of the myotendinous junction of the medial gastrocnemius muscle (MG) and marked its position on the dermal surface (P_{D-MG0}). Achilles tendon insertion (P_{A0} , **Fig.1-B**) onto the calcaneus bone was detected by ultrasonography and the nearest point on the dermal surface to P_{A0} was defined as P_{D0} . The center of the popliteal fossa (P_{Dpop}) was visually detected and marked on the dermal surface. The plane (PL), which included P_{D0} and P_{Dpop} and was perpendicular to the ground, intersected with the posterior surface of the right calf to make the dividing line (L_{div}). The intersection point, made by L_{div} and the plane perpendicular to PL and included P_{D-MG0} , was defined as P_{Dj} . The nearest point on the Achilles tendon to P_{Dj} was defined as P_{Aj} . From P_{D0} toward P_{Dj} , we placed small markers every ~ 1 cm on the dermal surface (**Fig.1-B**). The i -th point from P_{D0} was defined as P_{Di} . The nearest point on the Achilles tendon to P_{Di} was defined as P_{Ai} . These arrangements were executed while subjects were relaxed.

2.3. Two Conditions: Relaxed and Contracted

Tests were executed under the following two conditions. (1) relaxed: the ankles of subjects were passively moved at $5^\circ/\text{s}$ with the range of motion between 80 and 125° while legs were completely relaxed. (2) contracted: after a warm-up session, subjects were instructed to exert isometric torque from relaxation to maximal voluntary contraction (MVC) with a ramp

Fig. 1-A

Fig. 1-B (a, b)

Fig. 1. Experimental setup (Fig.1-A) and schematic illustration of the Achilles tendon with analyzed area (Fig.1-B; a: at rest; b: during contraction). In Fig.1-B, black small markers indicated by the black arrow are attached onto the dermal surface to analyze the coordinates of the dermal surface in the camera coordinate system.

increase in torque at $\sim 10\%$ MVC/s while their ankles were fixed at 90° . At this rate of force increment, we assumed that viscous properties of tendons are not substantial [Bennett et al. (1986), Herrick et al. (1978), Ker (1981), Lieber et al. (1991)]. The measurement was repeated twice. Kinematic and ultrasonographic data (see below) were calculated every 10% of MVC from rest to MVC. Under each of these two conditions, two tests (one for kinematic data and the other for ultrasonographic data) were executed.

2.4. Determination of the Coordinates of the Markers on the Dermal Surface (P_{Di}) Using Camera: Test 1 (relaxed) and 2 (contracted)

We videotaped the subjects' cruris from the left side at 200 frames/s (MEMRECAM C2S, Nac, Tokyo, Japan). The camera was set so that the optical axis of the camera was perpendicular to PL. From the video data, the coordinates of P_{Di} were calculated.

2.5. Determination of the Distance between the Dermal Surface and the Achilles Tendon Using Ultrasonography: Test 3 (relaxed) and 4 (contracted)

After removing the markers on the dermal surface, the ultrasonographic probe was fixed along L_{div} with fine wires set between the probe and the dermal surface. The fine wires were set to detect the position of P_{Di} in ultrasonographic images (Fig.2). The distance (d_i) between P_{Di} and P_{Ai} was measured on ultrasonographic images. Since the length of the probe was smaller than that between P_{D0} and P_{Dj} , tests were executed twice or three times to cover the analyzed area (Fig.1-B).

2.6. Estimation of the Achilles Tendon Length

From the results of test 2 and 4, we determined the coordinates of the Achilles tendon surface in the camera coordinate system in the following process. First, we drew a line (L_i) that included P_{Di} and was perpendicular to the line $P_{Di}P_{Di+1}$. Second, on the L_i , we plotted P_{Ai} that was d_i away from P_{Di} . Thus, P_{Ai} was the point on the Achilles tendon determined by the coordinates of the dermal surface's point (P_{Di}) and the distance between the dermal surface and the tendon. Finally, the Achilles tendon length between P_{A0} and P_{Aj} was calculated by summing up the segment length of $P_{Ai}P_{Ai+1}$.

2.7. Comparison between the Achilles Tendon Length Relaxed and Contracted

In the contracted condition described above, "isometric contraction" was conducted. However, a small change in the ankle angle was observed during contraction, which could be induced by mechanical compliance of the myometer and/or the subjects' limb deviation from the myometer [Muramatsu et al. (2001)]. In the present study, the Achilles tendon length in relaxed and contracted conditions was compared in the same ankle angle. In test 2, ankle angle, which was defined as the angle made by the point on the tibia, medial malleolus and P_{D0} , was measured on the images recorded by camera every 10% of MVC from rest to MVC. We then found, in test 1, the image whose ankle angle was most close to each of these 11 images of test 2. After estimating the Achilles tendon length as was described above, we compared the length in relaxed and contracted conditions (Fig.1-B). The following three facts were confirmed:

- (1) The position of P_{D0} was identical for relaxed and contracted conditions.
- (2) The horizontal position of P_{Dj} was identical for relaxed and contracted conditions,

Fig. 2. A typical longitudinal ultrasonographic image of the Achilles tendon at distal part.

note: This image is used, along with the camera data, to estimate the coordinates of the Achilles tendon surface in the coordinate system defined by the camera. The white arrow "Marker" indicates the position of the marker attached on the dermal surface to confirm the relative position of the ultrasonographic probe on the dermal surface

- (3) The vertical position of P_{Dj} was different for relaxed and contracted conditions, but the difference was negligible compared with the distance between P_{D0} and P_{Dj} .

Based on these facts, we could assume that the change of the Achilles tendon length in the analyzed area (Fig.1-B) between P_{D0} and P_{Dj} would result in the displacement of the myotendinous junction. If the curved path of the Achilles tendon becomes straight, the Achilles tendon length between P_{D0} and P_{Dj} decreases, pushing out the myotendinous junction proximally. Thus, the present method could clarify the effect of the change in the Achilles tendon path due to muscle contraction on the displacement of the myotendinous junction.

3. Results

Figure 3 shows the Achilles tendon length change compared with the relaxed condition within the analyzed area (between P_{D0} and P_{Dj}) at each torque exertion. "-1%" means that the Achilles tendon length within the analyzed area decreased by 1% compared with the relaxed condition. In this case, the length equivalent to 1% was pushed out of the analyzed area proximally and consequently, the myotendinous junction moved proximally by the 1% length. We assumed that the displacement of the myotendinous junction during isometric contraction is not only due to tendon elongation but also due to change in the tendon path.

4. Discussion

The results of the present study indicate that the change of the Achilles tendon path due to isometric contractions moves the myotendinous junction proximally by ~1%, at the most, of the Achilles tendon

Fig. 3. Length change of the Achilles tendon within the analyzed area at each torque exertion level.

note: Values are presented as means $\pm$ SD.
 Note that the 'length' is not the entire length of the Achilles tendon but the length within the analyzed area depicted in Fig. 1-B. "-1%" means that the Achilles tendon length within the analyzed area decreased by 1% compared with relaxed condition.

length. Therefore, if we simply calculate the Achilles tendon strain based on the displacement of the myotendinous junction, we would overestimate strain by $\sim 1\%$. Muramatsu et al. (2001) reported that the maximal strain of the Achilles tendon during isometric contraction was 5.1%, which was calculated from displacement of the myotendinous junction. If the present result is adopted for their result, the maximal Achilles tendon strain would be $\sim 4\%$. Reported human tendon strain in vivo in other studies was only for the tibialis anterior muscle: 2.5% by electric stimulation [Maganaris and Paul (2000a)] and 3.1% by voluntary contraction [Maganaris and Paul (2000b)]. In the two studies, they tightened the ankle by a bandage to eliminate the tendon path change, which might contribute to lessen overestimation of the tendon strain. Since the present method clarifies the effects of the tendon path change on the estimation of the tendon strain, the tendon strain during the movements with the tendon path change could be calculated.

In the present study, the resolution of the camera and ultrasonography is 0.54 and 0.67mm, respectively, whereas 1% of the mean Achilles tendon length at rest was 1.80mm. We assume that the resolution is fine enough to distinguish the Achilles tendon length

change. Individual variation (SD bar) is noticeable in Fig.3. In the present study, the ankle angle was 90° in the contracted condition. The degree of the Achilles tendon curving at this angle at rest could be different among subjects, which would vary the tendon path change during contraction. In Fig.3, the graph does not present a smooth curve, which suggests errors in data of the present study. We must therefore improve the method and decrease errors in future studies.

We could estimate the force exerted by a muscle if information on the tendon strain during muscle contractions was available, since tendon has an intrinsic force-strain property and is serially connected to the muscle. Previous studies on the human tendon strain in vivo [Maganaris and Paul (2000a, b), Muramatsu et al. (2001)] which assumed that displacement of the myotendinous junction is equal to the tendon strain, could be conducted only for isometric movements. In other types of movements, tendon strain could not be estimated by this method because joint angle change induces the movement of the myotendinous junction [Muramatsu et al. (2001), Muraoka et al. (2002)]. If we combine the information on the myotendinous junction movement and the present method, we could estimate the entire Achilles tendon length, whereby tendon strain during movements with joint angle change could be predicted. This implies that the force exerted during physical activity could be estimated noninvasively. That is, the relationship between force applied to the tendon and tendon strain is estimated in the isometric movement beforehand. Using this relationship, tendon strain during physical activity is estimated to calculate force applied to the tendon. Forces exerted by muscles have been measured by implanted apparatus [Fukashiro et al. (1993, 1995)] or by inverse dynamics [Zajac and Gordon (1989)]. The former method is invasive and operation on human in vivo is difficult for ethical reasons. In the latter method, even when the joint moment is accurately estimated, elimination of the influence of the synergistic muscles or antagonistic muscles is difficult. The method using tendon strain is free from these problems and will contribute to the estimation of the force exerted by muscles during physical activity.

The present study focused on the method estimating the human tendon strain in vivo in the light of tendon path change during contraction. It is suggested that tendon path change should be taken into account when tendon strain is calculated from myotendinous junction movements. The present method with more accuracy would contribute to estimating tendon strain and force during physical activity.

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Main Works:

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- Japan Society of Exercise and Sports Physiology
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- Japan Society of Physical Fitness and Sports Medicine
- Japan Society on Tennis Science
- Japanese Society of Biomechanics
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