Effects of isometric training on the elasticity of human tendon structures in vivo

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Kubo, Keitaro, Hiroaki Kanehisa, Masamitsu Ito, and Tetsuo Fukunaga. Effects of isometric training on the elasticity of human tendon structures in vivo. J Appl Physiol 91: 26–32, 2001.—The present study aimed to investigate the effect of isometric training on the elasticity of human tendon structures. Eight subjects completed 12 wk (4 days/wk) of isometric training that consisted of unilateral knee extension at 70% of maximal voluntary contraction (MVC) for 20 s per set (4 sets/day). Before and after training, the elongation of the tendon structures in the vastus lateralis muscle was directly measured using ultrasonography while the subjects performed ramp isometric knee extension up to MVC. The relationship between the estimated muscle force and tendon elongation (L) was fitted to a linear regression, the slope of which was defined as stiffness of the tendon structures. The training increased significantly the volume (7.6±4.3%) and MVC torque (33.9±14.4%) of quadriceps femoris muscle. The L values at force production levels beyond 550 N were significantly shorter after training. The stiffness increased significantly from 67.5±21.3 to 106.2±33.4 N/mm. Furthermore, the training significantly increased the rate of torque development (35.8±20.4%) and decreased electromechanical delay (−18.4±3.8%). Thus the present results indicate that isometric training increases the stiffness and Young’s modulus of human tendon structures as well as muscle strength and size. This change in the tendon structures would be assumed to be an advantage for increasing the rate of torque development and shortening the electromechanical delay.

resistance training; stiffness; ultrasonography; vastus lateralis muscle

RESISTANCE TRAINING INCREASES muscle size and strength (9, 22). However, we have little knowledge about the influences of resistance training on human tendon structures. The findings of previous research using animals indicated that chronic exercises could change the elastic properties of tendon and/or ligament tissues (27, 34). For example, Woo et al. (34) indicated that the ultimate strength and stiffness of tendon in pigs increased through 12 mo of endurance training. With regard to human tendon structures, however, available information on the subject is limited to the cross-sectional observations (13, 18). Kubo et al. (13) observed that the tendon structures of vastus lateralis (VL) muscle in long-distance runners were less compliant. These findings suggest that the elastic profiles of human tendon structures will be changeable through the execution of regular exercises, as observed in the animal experiments.

Previous studies indicated that strength training altered the rate of force production (9, 22) and electromechanical delay (36). For example, Narici et al. (22) reported that a significant decrease in time to peak torque was observed after strength training on knee extensors. They suggested that this observation could indicate an increase in the stiffness of the muscle-tendon complex. Furthermore, as suggested by Wilson et al. (32), an increase in the stiffness of the muscle-tendon complex should result in a higher force and rate of force development. A stiffer muscle-tendon complex would also transmit force to the bone more rapidly, and thus a higher rate of force development would be expected. Inversely, our laboratory’s recent observation demonstrated that the bed rest for 3 wk induced the changes in rate of torque development and electromechanical delay as well as tendon properties (12).

Recent advances in ultrasonographic analysis make it possible to determine the dynamics of human muscle-tendon complex in vivo (8, 12–16, 19). Kubo et al. (12–16) and Maganaris and Paul (19) have shown that ultrasonography was useful for determining the stiffness and Young’s modulus of human tendon structures in vivo. In the present study, the elongation of the tendon structures of the VL muscle in vivo was directly measured using ultrasonography before and after 12 wk of isometric training while the subjects performed ramp isometric knee extension up to maximal voluntary contraction (MVC). The purpose of the present study was to investigate the effects of isometric training on the elasticity of human tendon structures in vivo.

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METHODS

Subjects

Eight healthy men [age 22.6 ± 2.8 (SD) yr, weight 71.5 ± 6.1 cm, weight 69.2 ± 5.8 kg] voluntarily participated in this study. The subjects were physically active but had not performed in any organized program of regular exercise for at least 1 yr before testing. The subjects were fully informed of the procedures to be utilized as well as the purpose of this study. Written informed consent was obtained from all subjects. This study was approved by the office of Department of Sports Sciences, University of Tokyo, and complied with their requirements for human experimentation.

Magnetic Resonance Imaging

Measurements of muscle and tendon cross-sectional areas (CSAs) were carried out by magnetic resonance imaging scans (Resona, 0.5 Tesla System, General Electric). T1-weighted spin-echo, axial-plane imaging was performed with the following variables: 450-ms relaxation time, 20-ms echo time, 256 × 172 matrix, 300-mm field of view, 10-mm slice thickness, and 0-mm interslice gap. The subjects were imaged in a prone position with the knee kept at 90°. Coronal plane images were then taken to identify the anterior superior spine iliaca, which is the origin of the sartorius. Consecutive axial images were obtained from the anterior superior spine iliaca to the extremitas distal of the tibia. The number of axial images obtained for each subject was 43–48. The muscles investigated were as follows: rectus femoris (RF), VL, vastus intermedius (VI), and vastus medialis (VM). From the series axial images, outlines of each muscle were traced, and the traced images were transferred to a Macintosh computer (Power Macintosh 7200/120, Apple Computer) for calculation of the anatomic CSA using a public domain National Institute of Health Image software package. The muscle volume was determined by summing the anatomic CSA of each muscle times the thickness (10 mm). In addition, the measurement of tendon CSA was taken at two positions (one above the patella and the other at 10 mm proximal from the patella), although it was rather difficult to distinguish between tendon structures and other tissues in magnetic resonance images. The average of CSA at two positions was calculated as the representative of tendon CSA.

The repeatability for the muscle volume and tendon CSA measurements was investigated on 2 separate days over a period of 12 wk in a preliminary study with six young men (24.2 ± 3.1 yr, 169.5 ± 4.8 cm, 70.3 ± 5.4 kg). There were no significant differences between test and retest values of muscle volume and tendon CSA. The test-retest correlation coefficient was 0.95 for muscle volume and 0.97 for tendon CSA. The coefficient of variation was 2.1% for muscle volume and 1.6% for tendon CSA.

Measurement of Elastic Properties of Tendon Structures

Measurement of force. Each subject was seated on a test bench of a dynamometer with the hip joint angles of 80° flexed (full extension = 0°). The axis of the lever arm of the dynamometer was visually aligned with the center of rotation of the knee joint. The right ankle was firmly attached to the lever arm of the dynamometer with a strap and fixed with the knee joint angles of 80° flexed (full extension = 0°). After a standardized warm-up and submaximal contractions to be accustomed to tests, the subjects exerted isometric knee extension torque from zero (relax) to MVC within 5 s. The task was repeated twice per subject with at least 3 min between trials. Torque signals were analog-to-digital converted at a sampling rate of 1 kHz (MacLab/8, type ML780, AD Instrument) and analyzed by a computer (Macintosh Performa 630, Apple). The measured values that are shown below are the means of two trials.

Measurement of elongation of tendon structures. A real-time ultrasonic apparatus (SSD-2000, Aloka) was used to obtain a longitudinal ultrasonic image of the VL muscle at the level of 50% of thigh length, i.e., the length from the greater trochanter to the lateral epicondy of the femur. The ultrasonic images were recorded on videotape at 30 Hz, synchronized with recordings of a clock timer for subsequent analyses. The investigator visually confirmed the echoes from the aponeurosis and VL fascicles. The point at which one fascicle was attached to the aponeurosis (P) was visualized on the ultrasonic image. The P moved proximally during isometric torque development up to maximum (Fig.1). A marker (X) was placed between the skin and the ultrasonic probe as the landmark to confirm that the probe did not move during measurements. The cross-point between superficial aponeurosis and fascicles did not move. Therefore, the displacement of P (L) is considered to indicate the lengthening of the deep aponeurosis and the distal tendon (12–16).

Calculation of the elastic properties The knee joint torque (TQ) measured by the dynamometer was converted to muscle force (Fm) by the following equations

\[ F_m = k \cdot F_t \]

where \( F_t \) and \( k(0.28 \pm 0.03; \text{range } 0.21–0.33) \) represent, respectively, tendon force and relative contribution of VL to the quadriceps femoris muscles in terms of the ratio of the muscle volume, and \( MA (44.1 \pm 1.9 \text{ mm}; \text{range } 42.8–45.7 \text{ mm}) \) is the moment arm length of quadriceps femoris muscles at 80° of knee flexion, which is estimated from the thigh length of each subject as described by Visser et al. (29).

In the present study, the Fm and L values above 50% of MVC were fitted to a linear regression equation, the slope of which was adopted as an index of stiffness (12–16). The intra-class correlation coefficient for the test-retest of stiffness measurement was 0.89. The coefficient of variances of stiffness measurement was 6.3%.

Stress applied on the tendon was estimated from Ft and tendon CSA. Strain was also estimated from the L value and the initial length of the tendon structures, which was estimated from the distance between the measurement site and estimated insertion of the muscle over the skin (15, 16).

Measurement of Electromyograph

Bipolar surface electrodes (5 mm in diameter) were placed over the bellies of VL, RF, VM and biceps femoris muscles with a constant interelectrode distance of 25 mm. Electromyographic signals (EMG) were transmitted to a computer (Macintosh Performa 630, Apple) at a sampling rate of 1 kHz. The EMG was full-wave rectified and integrated for the duration of the contraction (from relaxed to MVC; 4.9 ± 0.2 s) to give the integrated EMG.

Measurement of Rate of Torque Development and Electromechanical Delay

The rate of torque development and electromechanical delay of the VL were measured during a maximal isometric knee extension carried out as strongly and rapidly as possible at a knee joint angle of 80°. The subject was asked to perform a MVC against the attachment of ankle immediately after
the sign of experimenter. The MVC was held for ~2 s, during which time the subject was verbally encouraged to produce a maximal contraction. There was a 2-min recovery between contractions. The rate of torque development was calculated from 10 to 60% MVC of percent MVC-time curve, as previously described (5, 12, 14). The electromechanical delay was calculated as the time interval between the onset of EMG and torque development (12, 14, 37). The onset of torque development was defined as a rise of 1 Nm above the baseline level. The onset of EMG was defined as a ±15 μV deviation from the baseline level. The repeatability for the rate of torque development and electromechanical delay measurements was investigated on 2 separate days over a period of 12 wk in a preliminary study with 6 young men. There were no significant differences between test and retest values of the rate of torque development and electromechanical delay. The test-retest correlation coefficient was 0.91 for rate of torque development and 0.89 for electromechanical delay. The coefficient of variation was 4.8% for rate of torque development and 5.3% for electromechanical delay.

Training
Subjects trained four times per week for 12 wk. The training protocol involved isometric knee extensions at 70% MVC. Each subject was seated on a test bench of a dynamometer and fixed with the knee joint angles of 80° flexed. The training protocol involved four contractions of 20 s duration with a 1 min rest between each. The measurement of MVC was made every 2 wk to adjust the training load.

Statistics
Descriptive data include means ± SD. One-way ANOVA was used to analyze the data. The F ratio for main effects and interactions were considered significant at P < 0.05. Significant differences among means at P < 0.05 were detected using post hoc test.

RESULTS
Figure 2 shows the relative changes in the muscle volumes of knee extensors. The muscle volume of knee extensors increased significantly by 7.6 ± 4.3% (range 4.7–12.1%). Furthermore, the muscle volumes of RF, VL, VI, and VM increased significantly with relative gains of 7.9±4.5, 7.2±5.2, 8.4±6.0, and 6.5±3.3%, respectively. There were no significant differences in the relative increase in muscle volume among the constituents of quadriceps femoris muscle. Furthermore, no significant difference in the tendon CSA was found between before and after training (Table 1).
Figure 3 shows the relationships between Fm and L. The MVC increased significantly after training (33.9 ± 14.4%; Table 1). The L values above 550 N were significantly shorter after training than before. Estimation of initial tendon length (253 ± 14 mm) and measurement of tendon CSA provided the stress-strain relationship of tendon structures (Fig. 4). The stiffness and Young’s modulus (slope of stress-strain curve) increased significantly after training (Table 1). In addition, there were no significant differences in the activation levels (integrated EMG) of each knee extensor muscles between before and after training (Table 2).

The main result of this study was that isometric training increased the stiffness and Young’s modulus of human tendon structures as well as muscle volume and strength. To our knowledge, this is the first evidence that shows the effects of strength training on the elastic profiles of human tendon structures in vivo.

DISCUSSION

The main result of this study was that isometric training increased the stiffness and Young’s modulus of human tendon structures as well as muscle volume and strength. To our knowledge, this is the first evidence that shows the effects of strength training on the elastic profiles of human tendon structures in vivo.

**Table 1. Measured parameters before and after training**

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td>MVC, Nm</td>
<td>219 ± 37</td>
<td>310 ± 45*</td>
</tr>
<tr>
<td>Maximum L, mm</td>
<td>32.6 ± 3.7</td>
<td>31.9 ± 3.7</td>
</tr>
<tr>
<td>Tendon CSA, mm²</td>
<td>212 ± 18</td>
<td>215 ± 21</td>
</tr>
<tr>
<td>Stiffness, N/mm</td>
<td>67.5 ± 21.3</td>
<td>106.2 ± 33.4*</td>
</tr>
<tr>
<td>Young’s modulus, MPa</td>
<td>288 ± 26</td>
<td>433 ± 35*</td>
</tr>
</tbody>
</table>

Values are means ± SD. MVC, maximal voluntary contraction; L, relationship between estimated muscle force and tendon elongation; CSA, cross-sectional area. *Significantly different from before, P < 0.05.

Before interpreting the present results, however, a mention should be made of the methodology used to determine the force production of the VL. We used the ratio of the VL to the quadriceps femoris in terms of muscle volume as the contribution of the muscle for force development. In addition, we estimated moment arm length from the data of the thigh length in each subject. To determine accurately the force production of the VL, however, the moment arm of each subject should be proposed. We cannot rule out that the variations in the moment arm length and/or relative contribution of the VL among subjects may influence the calculated force of the VL. In the present study, however, we aimed to investigate the effects of isometric training on the tendon properties rather than the force production of VL itself. In addition, it is noted that there were no significant differences between before and after training in the relative increase in the muscle volume and EMGs in each constituent of the quadriceps femoris (Fig. 2, Table 2). In addition, we also confirmed that little cocontraction of knee flexor muscles occurred during knee extension. This implies that the relative contribution of each constituent of the quadriceps femoris for force production was similar between before and after training. Therefore, we considered that the muscle force calculation based on the above-mentioned assumptions was valid to study the changes of the tendon properties after isometric training.

**Table 2. iEMG values during ramp isometric contraction**

<table>
<thead>
<tr>
<th></th>
<th>RF</th>
<th>VL</th>
<th>VM</th>
<th>BF</th>
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<tbody>
<tr>
<td>Before</td>
<td>1.37 ± 0.46</td>
<td>1.54 ± 0.31</td>
<td>1.48 ± 0.42</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td>After</td>
<td>1.45 ± 0.51</td>
<td>1.61 ± 0.29</td>
<td>1.55 ± 0.38</td>
<td>0.12 ± 0.02</td>
</tr>
</tbody>
</table>

Values are means ± SD given in mVs. iEMG, integrated electromyograph; RF, rectus femoris; VL, vastus lateralis; VM, vastus medius; BF, biceps femoris.
cumulative damage. On the other hand, Wang et al. (31), suggesting that tendon failure would result from fatigue test, but much faster just before rupture (25, 30, 31). Some researchers showed that the mean extension of the wallaby tail tendons increased slowly during the fatigues before failure and the ultimate load of the peroneus brevis tendons of rabbits were higher for animals trained for 40 wk than for untrained animals but that the mass as well as water and collagen content of these tendons were not different. Similarly, Rollhauser (24) reported that, although no increase in the thickness of tendon of trained pigs for 42 days were observed, its tensile strength increased up to 12%. Taking the presents result into account together with the above-mentioned findings, it is likely that the tendon structures of VL do not modify easily their masses and/or collagen concentrations by only 12 wk of training.

The mechanisms that resulted in the increase in the stiffness and Young's modulus remain unknown, although the training did not induce a significant hyperrophic change in tendon structures. As an explainable reason for the increased stiffness and Young's modulus, it might be hypothesized that the training induced the changes in the internal structures of tendon and/or aponeurosis. Rollhauser (24) pointed out that, as a result of 42-day training for pigs, the only way that mature tendons could make positive responses to the chronic exercise was to improve the internal structures of tendons. In fact, previous research using various animal models have provide evidence suggesting that excessive loading changes in the internal structures of tendons (20, 35). For example, Michna (20) demonstrated that the physical loading induced to rodent tendons caused the changes in the degree of alignment of the constituent collagen fibers. Again, the findings of Zamora and Marini (35) indicated that an overload model of the rat plantaris tendon by removing its synergists disrupted the collagen bundles of tendon and emptied longitudinal spaces. The variability of the mechanical quality of collagen originates from differences in either the cross link pattern of the collagen or the structure and packing of the collagen fibers (7). Some researchers showed that the mean extension of wallaby tail tendons increased slowly during the fatigues test, but much faster just before rupture (25, 30, 31), suggesting that tendon failure would result from cumulative damage. On the other hand, Wang et al. (31) have suggested that “remodeling” process of the tendon architecture may be involved during a transient period of mechanical weakness. Recently, our laboratory observed that the repeated muscle contractions changed the human tendon structures to be more compliant as an acute effect (14). If the remodeling process as suggested by Wang et al. (31) can be applied to the present results, therefore, the observed changes in the stiffness and Young's modulus after training might be explained as a result of changes in the internal structures of tendons for compensating the mechanical weakness induced by the repeated loading.

In the present study, the stress of tendon structures at MVC (22–31 MPa) was in agreement with the finding of Maganaris and Paul (19). Furthermore, the Young's modulus values (before, 288 MPa; after, 433 MPa) were in line with the previous observations (15, 16) but substantially lower than those previously reported for animal and human cadaver tendons (2, 33, 34). This discrepancy can be attributed to the fact that the Young's modulus value determined in the present study represents the elasticity of both outer tendon and aponeurosis, whereas the above-mentioned research on Young's modulus investigated the outer tendon only (2, 33, 34). In addition, the strain of 12.8% at maximum tendon stress was greater than the values reported by Kubo et al. (15) and Lieber (17). The reason for this discrepancy would be the movement of patellar and tibial bone during contraction but only at lower force levels (<50% MVC; Ref. 16).

It is documented that strength training increases the rate of force production (9, 22). Hakkinen et al. (9) showed that the strength training of knee extensors for 24 wk made the time to reach maximal force levels decrease. Similarly, Narici et al. (22) reported that a significant decrease in time to peak torque was observed after strength training on knee extensors. In this study, too, the rate of torque development significantly improved after training. The rate of torque development depends both on the stiffness of the series elastic component and on the force-velocity characteristics of the contractile component (11). Certainly, some previous studies demonstrated that the muscle strength gain at the beginning of resistance training was due to an improved activation level (1, 21). On the other hand, the stiffer tendon structures are suitable for transmitting the force to tendon more effectively (6), and so an increase in the stiffness of muscle-tendon complex should result in a higher force and improve the rate of force development (32). Considering these findings, therefore, it is reasonable to assume that the observed increase in the stiffness of tendon structures may be a reason for both MVC torque and the rate of torque development under isometric contractions.

In addition to the changes in the rate of torque development, the electromechanical delay significantly shortened after training. Some researchers have found that the electromechanical delay is correlated to the MVC, rate of force development, and muscle fiber composition (23, 28). It was not likely that the muscle fiber composition of the trained muscles changed through 12
wk of isometric training (26). So far, few studies have investigated the chronic effects of training on electromechanical delay. Among the limited studies, Hakkinen and Komi (10) have failed to found a significant change in the electromechanical delay under a reflex contraction after a 16-wk strength training. Again, Zhou et al. (37) reported that the 7 wk of sprint training did not change significantly the electromechanical delay of knee extensor muscles. On the other hand, a cross-sectional observation on athletes indicated that the electromechanical delay of weight lifters has been found to be significantly shorter than that of endurance athlete (36). The electromechanical delay refers to the time lag between the onset of electrical activity and tension development in skeletal muscle. It appears that the electromechanical delay is composed of several processes, such as excitation-contraction coupling, contraction of the contractile component, and stretching of the series elastic component. Hence, the possible differences in the adaptation of these variables to training, which would be attributed to the content of exercise regimens used, might explain the variability between the results of the present and previous studies. As far as the present results are concerned, we may conclude that the increase in the stiffness of tendon structures, which means an increase in the ability to transmit muscle force more effectively (e.g., Ref. 6), plays an important role in shortening the electromechanical delay. In any case, the shortened electromechanical delay as well as the increased stiffness after training will be considered to be suitable changes for improving muscle performances during various rapid movements.

In conclusion, the present results suggest that the isometric training for 12 wk resulted in an increase in the stiffness and Young’s modulus of tendon structures as well as muscle strength and volume. This change in the tendon structures would be assumed to be an advantage for increasing the rate of torque development and shortening the electromechanical delay.

REFERENCES


