Effect of low-load resistance training on the tendon properties in middle-aged and elderly women

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Abstract
Aim: The purposes of this study were to determine the age-related changes in the tendon-aponeurosis structures and to investigate the effects of low-load resistance training on the tendon-aponeurosis structures in middle-aged and elderly women.

Methods: Fifty-one women (55.8 ± 13.7 years, range: 21–77 years) volunteered to take part in the present study. Furthermore, 11 middle-aged and elderly women (49.7 ± 9.2 years) performed the low-load resistance training, i.e. squat using body weight, for 6 months. The elongation of the tendon and aponeurosis of the vastus lateralis muscle was directly measured by ultrasonography, while the subjects performed ramp isometric knee extension up to the voluntary maximum, followed by a ramp relaxation. The relationship between the estimated muscle force \( F_m \) and tendon elongation \( L \) during the ascending phase was fitted to a linear regression, the slope of which was defined as stiffness. The percentage of the area within the \( F_m-L \) loop to the area beneath the curve during the ascending phase was calculated as hysteresis.

Results: Maximal strain \( L/\text{initial tendon length} \) and stiffness of the tendon-aponeurosis structures decreased significantly with ageing. In contrast, the hysteresis increased significantly with ageing. In addition, low-load resistance training produced no significant change in stiffness and hysteresis, but significantly increased the maximal elongation of tendon-aponeurosis structures from 23.3 ± 2.1 mm to 24.8 ± 2.2 mm \( (P = 0.045) \).

Conclusion: These results suggest that increasing age results in a decrease in the elasticity of tendon-aponeurosis structures and an increase in their viscosity. Furthermore, the low-load resistance training made the elasticity of tendon-aponeurosis structures increase.

Keywords elderly, human, resistance training, tendon, ultrasonography.

It is well established that there is an age-related decrease in voluntary static and dynamic strength in the lower limb muscles (Hakkinen & Hakkinen 1991, Lindle et al. 1997, Akima et al. 2001). In addition, explosive strength characteristics may decline with increasing age even more than maximal strength (Larsson et al. 1979, Bosco & Komi 1980, Vito et al. 1998). For example, Bosco & Komi (1980) showed a tendency towards a reduction of the differences between squat jump and counter-movement jump with ageing, attributing this result to the changes in the properties of muscle and tendon. In other words, the age-related changes in the tendon properties would lead to the decline in the utilization of the elastic energy. Information on the age-related changes in the viscoelastic properties of tendon structures in vivo is essential to understand the changes in these muscle functions, because the tendon properties affect performance during stretch-shortening cycle exercises (e.g. Kubo et al. 1999, 2000). However, no report has so far been available regarding the changes in the tendon properties with ageing when tested experimentally in humans.

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The decreased muscle strength of elderly individuals is at least partly reversible by resistance training (Moritani & DeVries 1980, Frontera et al. 1988, Hakkinen et al. 2000). Resistance training clearly promotes muscle fibre hypertrophy in young individuals (e.g. McDonagh & Davies 1984), and recent evidences suggest that increased strength in elderly individuals reflect muscle hypertrophy (e.g. Frontera et al. 1988). Frontera et al. (1988) showed that older leg muscles could respond to intense resistance training with significant increases in muscle and muscle fibre size. On the other hand, the resistance training with heavy load would have risk for the elderly individuals. However, a few studies have investigated the effect of resistance training with light loads on muscle strength and mass (Aniassson & Gustafsson 1981, Agre et al. 1988, Heinonen et al. 1993, Moss et al. 1997). For example, Aniassson & Gustafsson (1981) showed that elderly women (69–74 years) increased the maximal knee extension torque by 9–22% with a 12-week training programme using body weight as resistance.

Nowadays, the number of elderly people who participate in sports is increasing in those societies with the longest average life expectancy. This increasing participation in sport among the elderly can also be seen in the increasing number of competitors in international games for elderly athletes. As a consequence, injuries from overuse, which have generally been described in the competitive athletes, are now becoming recognized in the elderly population (Kallinen & Markku 1995). In earlier studies, it was found that sports-related injuries were very common among elderly athletes (Pollock et al. 1991, Carroll et al. 1992). As a main reason for this, it has been postulated that the tendon structures in elderly people is less able to cope with repetitive biomechanical stress during various activities, as the tendon structures act as a mechanical buffer, protecting the muscle from damage during high-intensity contractions (Griffiths 1991, Lieber 1991). However, little is known about the effects of resistance training on the tendon properties in elderly individuals. Therefore, information on the age-related changes in the viscoelastic properties of tendon-aponeurosis structures in vivo is essential in order for elderly people to perform various kinds of training.

Recent reports have shown that ultrasonography can be used to determine the stiffness and hysteresis of human tendon-aponeurosis structures in vivo (Kubo et al. 1999, 2000, 2001, Maganaris & Paul 1999, Magnusson et al. 2001). However, no report has so far been available regarding the age-related changes in the viscoelastic properties of human tendon-aponeurosis structures in vivo. Furthermore, we have little knowledge on the influences of resistance training programmes on tendon structures in elderly people. The purposes of this study were to determine the age-related changes in the tendon properties and to investigate the effects of low-load resistance training on the tendon-aponeurosis structures in middle-aged and elderly women.

**Methods**

**Subjects**

Fifty-one women (age: 55.8 ± 13.7 years, height: 152.6 ± 5.1 cm, body mass: 52.6 ± 6.2 kg, mean ± SD) volunteered to take part in the present study. In addition, eighteen middle-aged and elderly women were studied to assess the effects of 6 months low-load resistance training on the viscoelastic properties of tendon structures. The subjects were assigned into a training group (n = 11; age: 49.7 ± 9.2 years, height: 156.0 ± 4.9 cm, body mass: 55.5 ± 7.4 kg) and a control group (n = 7; age: 48.4 ± 14.2 years, height: 152.7 ± 4.9 cm, body mass: 50.9 ± 2.7 kg). The subjects in the study were either sedentary, or mildly to moderately active women, but none were involved in any type of resistance exercise programme at the time of the study. The procedures, purpose and risks associated with the study were explained to all the subjects before they gave their written informed consent to participate in this investigation. This study was approved by the office of the Department of Sports Sciences, University of Tokyo, and complied with their requirements for human experimentation.

**Measurement of muscle thickness**

The thickness of the quadriceps femoris muscle was measured with an ultrasonic apparatus (SSD-5500; Aloka, Tokyo, Japan). A single cross-sectional image was obtained at a site 50% of the thigh length, i.e. the distance from the greater trochanter to the lateral epicondyle of the femur. At this level, mediolateral widths of the vastus lateralis (VL), vastus intermedius (VI) and rectus femoris (RF) were visualized by use of the ultrasound apparatus. The interfaces among the subcutaneous adipose, muscle and bone tissues were identified from the ultrasonic images. The distances between the adipose tissue-RF and RF-VI interfaces, and between the RF-VI-bone interfaces, and between the adipose tissue-VL and VI-VL interfaces were determined as the thickness values of RF (MTRF), VI (MTVI) and VL (MTVL). The sum of the thickness of the three muscles (RF, VI and VL) was adopted as representative of the muscle size of the quadriceps femoris muscles (MT).

**Measurement of viscoelastic properties of tendon structures**

Each subject was seated on a test bench of an electrical dynamometer (Vine, Tokyo, Japan) with the hip joint
angle flexed at 80°. The centre of rotation of the knee joint was visually aligned with the axis of the lever arm of the dynamometer. The right foot was firmly attached to the lever arm of the dynamometer with a strap and secured with the knee joint angle flexed at 80°. Prior to the test, the subject performed a standardized warm-up and submaximal contractions to become accustomed to the test procedure. The subject was instructed to develop a gradually increasing force from relaxed to maximal voluntary contraction (MVC) within 5 s, followed by a gradual relaxation within 5 s. Measurement was repeated twice per subject with at least 3 min between trials. Torque signal was A/D converted at a sampling rate of 1 kHz (MacLab/8, type ML780; AD Instrument, Tokyo, Japan) and analysed by a computer (Power Macintosh 7200/120; Apple Computer, Cupertino, USA). The measured values shown below are the mean values of two trials.

The ultrasonic apparatus was also used to obtain a longitudinal ultrasonic image of the VL at a level 50% of the thigh length during isometric contractions. The ultrasonic images were recorded on a video-tape at 30 Hz, synchronized with recordings of a clock timer for subsequent analyses. The tester visually confirmed the echoes from the aponeurosis and VL fascicles. The point at which one fascicle attached to the aponeurosis (P) was visualized on the ultrasonic image. The P moved proximally during the isometric torque development up to the maximum (Fig. 1). A marker (×) was placed between the skin and the ultrasonic probe as the landmark to confirm that the probe did not move during measurements. Because the cross-point between superficial aponeurosis and fascicles did not move during contractions, the displacement of P (L) was considered to indicate the lengthening of the deep aponeurosis and the distal tendon (Kubo et al. 1999, 2001). Strain was estimated from the L value and the initial length of the tendon structures, which was estimated from the distance between the measurement site and the estimated insertion of the muscle over the skin (Kubo et al. 1999, 2001, Magnusson et al. 2001).

The knee joint torque measured by the dynamometer was converted to muscle force ($F_m$) by the following equations:

$$F_t = \frac{TQ}{MA}$$

$$F_m = kF_t$$

where $F_t$ and $k$ represent the tendon force and the relative contribution of VL to the quadriceps femoris muscles in terms of physiological cross-sectional area, respectively (Narici et al. 1992), and MA is the moment arm length of the quadriceps femoris muscles at 80° of knee flexion, which is estimated from the thigh length of each subject as described by Visser et al. (1990).

**Figure 1** Ultrasonic images of longitudinal sections of the vastus lateralis muscle during isometric contraction. A marker (×) 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. The cross-point (P) was determined from the echoes of the deep aponeurosis and fascicles. The P moved proximally during isometric torque development from rest (P1) to 50% maximal voluntary contraction (P2). The distance travelled by P (L) was defined as the length change of tendon and aponeurosis during contraction.
In the present study, the \( F_m \) and \( L \) values above 50% of MVC were fitted to a linear regression equation, the slope of which was adopted as stiffness (Kubo et al. 1999, 2001). The percentage of the area within the \( F_m-L \) loop to the area beneath the curve during the ascending phase was calculated as hysteresis. (Kubo et al. 2001).

A comparison of stiffness and hysteresis values between the two measurements for all the subjects revealed no significant difference; an interclass correlation of \( r = 0.89 \) and 0.85, and a coefficient of variation of 5.7 and 9.6%.

**Resistance training**

Eleven subjects participated in a low-load squat training using body weight for 6 months. The squat begins with the individual in the upright position with the knees and hips fully extended. The individual then squats down in a continuous motion until a desired squat depth (the thigh is parallel to the floor) is obtained and then in a continuous motion ascends back to the upright position. This training session (50 repetitions day\(^{-1}\)) was performed on a daily basis for six consecutive months. The actual number of repetitions was 44±17 repetitions day\(^{-1}\), and the actual participation was 5.7±0.9 days week\(^{-1}\). All of the training sessions were preceded by a 10-min static stretching routine for the different muscles of the legs (hip flexors and extensors, knee extensors, plantar flexors, etc.).

The control subjects (\( n = 7 \)) were instructed to continue their daily routines and not to change their physical activity level.

**Statistics**

Descriptive data included mean ± SD. Pearson product–moment correlation analysis was used to assess the relationships between age and the measured variables. The significance of difference between before and after training was analysed by a paired Student’s \( t \)-test. The level of significance was set at \( P < 0.05 \).

**Results**

Figure 2 shows the age-associated decline of MVC and MT. MVC decreased significantly with age (\( r = 0.423, P < 0.01 \)). The correlation coefficient obtained by comparing age and MT was negative and significant both when MT was expressed in absolute (Fig. 2b; \( r = 0.449, P < 0.01 \)) and relative values (to limb length; \( r = 0.362, P < 0.01 \)). Age accounted for 18% of the variance for MVC and 20% for MT.

Figure 3 shows the age-associated differences in maximal strain, stiffness and hysteresis. The maximal strain and stiffness decreased significantly with age with correlation coefficients of −0.338 (\( P < 0.05 \)) and −0.381 (\( P < 0.01 \)), respectively. In contrast, the hysteresis increased significantly with age with a correlation coefficient of 0.371 (\( P < 0.01 \)). Age accounted for 11% of the variance for maximal strain, 15% for stiffness and 14% for hysteresis.

In the control group, no significant changes in MVC, MT and the tendon properties were found (Table 1). MVC in the trained group increased significantly after training (9.7%; \( P = 0.036 \)), although MT did not change (\( P = 0.305 \)). The measured parameters are shown in Table 1. The maximal strain increased significantly (7.1%; \( P = 0.045 \)). However, there were no significant differences in stiffness and hysteresis between before and after training (\( P = 0.190 \) for stiffness, \( P = 0.271 \) for hysteresis).
Discussion

An interesting finding of this study was that the declines in maximal strain and stiffness of the tendon structures and the increment in hysteresis with ageing were significant. These age-related changes in the tendon properties would lead to decline in the capacity to store and utilize the elastic energy compared with younger individuals. Previous findings obtained from animal experiments have shown that the ultimate strength and Young’s modulus of tendon and ligament decrease with increasing age (Noyes & Grood 1976, Blevins et al. 1994). For example, Noyes & Grood (1976) showed that the maximum stress, elastic modulus and strain energy for the preparation were negatively correlated with age. Nakagawa et al. (1994) reported that the mean area and diameter of collagen fibres decreases as does the number of thick fibres. Furthermore, age-related increases in connective tissue and collagen cross-linking have been reported that might decrease the elasticity of tendon structures during muscle contractions (Alnaqueeb & Goldspink 1986, Lexell & Downham 1991). Therefore, the declines in maximal strain and stiffness in this study agreed with these previous findings using animal and human cadavers.

On the other hand, the hysteresis, i.e., the area within the loop, represents the energy loss as heat as a result of internal damping, while the area under the unloaded curve is the energy recovered in the elastic recoil (Butler et al. 1978). The increment in hysteresis with age would imply that the elderly person recovered less elastic energy during the stretch-shortening cycle exercises, i.e. walking, running and jumping. However, the mechanisms which result in the increase of hysteresis with age are unknown. At least for the increased hysteresis with age, a change in the structure of the tendons might be involved.

Recently, we observed that the hysteresis of tendon structures in the knee extensors and plantar flexors increased significantly after 3 weeks of bed rest (Kubo et al., unpublished data). Inversely, we reported that acute and chronic static stretching made the hysteresis of tendon structures decrease (Kubo et al. 2001, 2002). Further, density and structure of cross-links and the fibril morphology in collagenous tissues changes as a function of age, in a manner that can be correlated with age-related changes in mechanical properties (Noyes & Grood 1976, Parry et al. 1978, Viidik 1982).

Table I Measured variables before and after training. Mean (SD)

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<th>Before</th>
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<tr>
<td>MVC (Nm)</td>
<td>81.8 (14.1)</td>
<td>89.1 (14.2)*</td>
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<tr>
<td>Muscle thickness (mm)</td>
<td>69.7 (9.8)</td>
<td>70.7 (7.6)</td>
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<tr>
<td>Maximal L (mm)</td>
<td>23.3 (2.1)</td>
<td>24.8 (2.2)*</td>
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<tr>
<td>Maximal strain (%)</td>
<td>11.8 (1.4)</td>
<td>12.5 (1.5)*</td>
</tr>
<tr>
<td>Stiffness (N/mm)</td>
<td>23.5 (6.3)</td>
<td>27.2 (10.2)</td>
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<tr>
<td>Hysteresis (%)</td>
<td>19.6 (8.9)</td>
<td>18.1 (7.8)</td>
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<th></th>
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<tr>
<td>MVC (Nm)</td>
<td>73.5 (26.4)</td>
<td>71.3 (20.9)</td>
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<tr>
<td>Muscle thickness (mm)</td>
<td>63.6 (9.3)</td>
<td>61.5 (7.1)</td>
</tr>
<tr>
<td>Maximal L (mm)</td>
<td>21.8 (3.2)</td>
<td>21.3 (3.8)</td>
</tr>
<tr>
<td>Maximal strain (%)</td>
<td>11.1 (1.7)</td>
<td>10.8 (2.8)</td>
</tr>
<tr>
<td>Stiffness (N/mm)</td>
<td>24.9 (9.1)</td>
<td>23.6 (5.7)</td>
</tr>
<tr>
<td>Hysteresis (%)</td>
<td>23.2 (12.9)</td>
<td>21.4 (7.5)</td>
</tr>
</tbody>
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*Significantly different from before.
Some previous studies have shown that the explosive strength and/or performance during the stretch-shortening cycle decline with increasing age (Larsson et al. 1979, Bosco & Komi 1980, Vito et al. 1998). For example, Bosco & Komi (1980) showed a tendency towards a reduction of the differences between squat jump and counter-movement jump with ageing. On the other hand, our recent observations have shown that the tendon properties affected the performances during the stretch-shortening cycle exercises (Kubo et al. 1999, 2000). Taking the present results into account, together with the above previous findings, it is likely that age-related changes in the tendon properties take place, which may explain the decrease observed previously in the performances during the stretch-shortening cycle exercises, i.e. elderly individuals would have a lesser capacity to store and utilize elastic energy compared with younger individuals.

In the present study, the muscle thickness did not change after low-load resistance training for 6 months, although the muscle strength increased significantly (9.7%). Some previous studies have demonstrated that the decreased muscle strength of elderly individuals is reversible by resistance training (Moritani & DeVries 1980, Frontera et al. 1988, Hakkinen et al. 2000). For example, Frontera et al. (1988) showed that older leg muscles could respond to intense resistance training with significant increases in muscle and muscle fibre size. On the other hand, a few studies have investigated the effect of resistance training with low loads on muscle strength and mass (Aniansson & Gustafsson 1981, Agre et al. 1988, Heinonen et al. 1993, Moss et al. 1997). In sedentary women, Heinonen et al. (1993) reported a significant increase in MVC after training with only 25% of IRM. In addition, Aniansson & Gustafsson (1981) showed that elderly women (69–74 years) increased the maximal knee extension torque by 9–22% with a 12-week training programme using body weight as resistance. Therefore, the present results agreed with these previous findings. Moritani & DeVries (1980) suggested that the increases in strength in older people would primarily result from considerable neural adaptations, particularly observed during the earlier weeks of resistance training as indicated by the increases in maximal electromyographic activity of the trained muscles. Therefore, it is likely that low-load resistance training has an effect on the improvement of the nervous system, not but on hypertrophy.

The present investigation is the first to demonstrate that the maximal strain of tendon structures is significantly increased with resistance training in middle-aged and elderly women. Certainly, it is not to be denied that the greater force has been able to applied to the tendon structures after the resistance training. However, there was no significant correlation between the relative increment of MVC and maximal strain ($r = -0.38$, ns). Given the increase in maximal strain observed in the present study, resistance training appears to offer an effective counter-measure to attenuate or reverse the decline in the extensibility of tendon structures that has been observed with old age. Rice et al. (1993) reported that the time to peak tension increased after dynamic strength training for 24 weeks in elderly men. They suggested that the resistance training caused increased compliance and, thus, slowing of the measured in vivo contractile times. Sale et al. (1982) observed a significant decrease in twitch tension after training and a significant increase in tetanic tension. These changes in the twitch-to-tetanus ratio may reflect alterations in the extensibility of the muscle–tendon complex (Sale et al. 1982). Therefore, a training-induced increase in the maximal strain of tendon structures may have caused a lower proportion of the maximal possible tension to be elicited, with the consequent decrease in twitch tension that was observed previously.

Considering these results, we may say that moderate exercises could reduce the risk of injury during recreational and athletic sports participation in elderly people. In earlier studies, it was found that sport-related injuries were very common among elderly athletes (Pollock et al. 1991, Carroll et al. 1992). Stretching is almost universally emphasized in pre-participation warm-ups, post-injury, post-operative rehabilitation and performance enhancement. However, our recent observation have shown that static stretching training for 3 weeks did not change the extensibility of the tendon structures (Kubo et al. 2002). It is well known that the tendon structures act as a mechanical buffer, protecting the muscle from damage during high-intensity contractions (Griffiths 1991, Lieber 1991). Therefore, the present result implies that the practice of moderate exercise, i.e. low-load resistance training, prevents injuries of the muscle and tendon in elderly people, compared with stretching exercises.

In conclusion, these results suggest that increasing age results in a decrease in the elasticity of tendon structures and an increase in their viscosity, i.e. elderly individuals would have a lesser capacity to store and utilize elastic energy compared with younger individuals. Furthermore, the low-load resistance training made the extensibility of tendon structures increase, although the muscle thickness did not change. Thus, moderate exercises could reduce the risk of injury during recreational and athletic sports participation in elderly people.

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