Age-Related Differences in the Force Generation Capabilities and Tendon Extensibilities of Knee Extensors and Plantar Flexors in Men

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Background. Recently, the number of elderly individuals who participate in sports has increased, thus injuries from overuse are now becoming recognized in the elderly population. Therefore, it is important to determine which muscle groups and tendons are most affected with aging to plan appropriate exercise interventions for elderly individuals. In particular, muscles and tendons in knee extensors and plantar flexors play an important role during locomotion. The purpose of this study was to compare the knee extensor and plantar flexor muscles and tendons.

Methods. Young (n = 19) and elderly (n = 17) men performed isometric voluntary knee extension and plantar flexion contractions. Muscle thickness and elongation of tendon structures in knee extensors and plantar flexors were measured by ultrasonography.

Results. Relative muscle thickness (to limb length) in the elderly group was significantly lower than that in the young group in knee extensors (p < .001), although no significant difference was found between the two groups in plantar flexors (p = .063). Relative muscle strength (to body mass) in the elderly group was significantly lower than that in the young group in both sites (all p < .001). Ratio of muscle strength to muscle thickness in the elderly group was significantly lower than that in the young group in plantar flexors, but not in knee extensors. The elderly group had significantly lower maximal elongation and strain of tendon structures in both sites than the young group had.

Conclusion. These results suggest that the age-related weakness in knee extensors may be attributed to muscle atrophy, whereas that in plantar flexors is not, and that elderly persons have less extensible tendon structures in both sites.

It is well known that muscle strength declines with aging [e.g., (1)]. In particular, the age-related decline in muscle strength is greater in the lower than upper limbs (2). Although this age-related decline in muscle strength is largely due to muscle atrophy (3,4), it is also caused by a reduction in the neural activation level (5,6). Some previous studies indicated that the loss of muscle strength with aging exceeds the decrease in muscle size (2,4,7). However, previous findings concerning the influence of aging on the ratio of muscle strength to muscle size are conflicting (3,4). For example, Davies and colleagues (7) and Morse and coworkers (6) reported that the ratio of muscle strength to the cross-sectional area of plantar flexors was significantly lower in elderly individuals than in young individuals, whereas Overend and colleagues (3) and Young and coworkers (4) did not observe any effects of aging in the cross-sectional area knee extensors. Thus, previous reports on the existence of age-related change in muscle strength in relation to muscle size differ between the muscles examined. At present, however, few studies have simultaneously assessed these variables in knee extensors and plantar flexors (8).

Some previous studies using animal and human cadavers showed that the failure load and Young’s modulus of tendons decreased with aging (9–11). Recently, we observed that the maximal strain of the human tendon structures in knee extensors decreased significantly with aging (12). On the contrary, Morse and colleagues (13) reported that the human gastrocnemius tendons of elderly participants were more compliant than those of young adults. Although the reasons for the discrepancy between the two reports are unknown, there is a possibility that age-related changes in the tendon properties would differ between the sites. However, no studies have so far been available regarding site differences in age-related changes in tendon properties.

Recently, the number of elderly individuals who participate in sports has increased, thus injuries from overuse are now becoming recognized in the elderly population (14). Therefore, it is important to determine which muscle groups and tendons are most affected with aging in order to plan appropriate exercise interventions for elderly individuals. In particular, muscles and tendons in knee extensors and plantar flexors play an important role during locomotion, that is, walking and running. The purpose of this study was to compare the mechanical and morphological properties of muscles and tendons in knee extensors and plantar flexors between two different age groups.
Methods

Participants

Nineteen young (22–35 years) and 17 elderly (62–77 years) men participated in this study. All men were recruited from the community and were healthy and living independently. They were also free from cardiovascular and/or metabolic disorders according to a standardized interview. The procedures, purpose, and risks associated with the study were explained to all participants, and they gave their written informed consent to participate in this investigation before starting this project. This study was approved by the Local Ethics Committee of the Department of Sports Sciences, University of Tokyo, and complied with their requirements for human experimentation. The physical characteristics of the participants are shown in Table 1. All participants were sedentary or mildly active, with none currently involved in any type of exercise program (> 30 min/d, > 2 d/wk).

Number of Steps

For a 2-week period, the number of steps per day of each participant was measured to document the physical activity level during daily life. Each participant put a pedometer (FB-714; Tanita, Tokyo, Japan) on his belt or waistband as soon as he woke up each morning, removed it before going to bed every night, and recorded the number of steps per day. The total number of steps each day was recorded on daily log sheets. In the present study, the mean number of steps during 2 weeks was used as an index of the physical activity level during daily life (6).

Muscle Thickness

The muscle thickness values for knee extensors (three anatomic sites: on the anterior surface 30%, 50%, and 70% of the distance between the lateral condyle of the femur and greater trochanter) and plantar flexors (three anatomic sites: on the posterior surface 20%, 30%, and 40% of the distance between the lateral malleolus of fibula and the lateral condyle of the tibia) were measured with an ultrasonic apparatus (SSD-900; Aloka, Tokyo, Japan). The muscles involved in the measurement of muscle thickness were as follows: rectus femoris and vastus intermedius muscles for knee extensors; lateral gastrocnemius, soleus, and tibialis posterior muscles for plantar flexors. The participants remained in a supine position for the measurement of knee extensors and in a prone position for the measurement of plantar flexors with legs straight and the muscles relaxed. The anthropometric locations of the measurement sites were first precisely determined and marked by experienced technicians before the ultrasonic measurement. A transducer with a 7.5 MHz scanning head was coated with water-soluble transmission gel, which provided acoustic contact without depressing the dermal surface. The interfaces between subcutaneous adipose tissue and muscle and between muscle and bone were identified from the ultrasonic image, and the distance from the adipose tissue–muscle interface to muscle–bone interface was measured as a representative of muscle thickness. The thickness of each site was measured to the nearest 0.1 mm using a Vernier caliper. The mean values of the muscle thickness at all the measured sites were adopted as their representative of each part. Because the elderly participants were shorter than their younger counterparts (as shown in Table 1), it was considered that the age-related differences observed in muscle thickness could be attributed to differences in body size. Therefore, absolute and relative (to limb length) muscle thickness values were presented (15). Furthermore, some previous studies demonstrated that the ultrasonographic approach used in the present study was useful for examining muscle volume (16,17).

Muscle Strength

Maximal voluntary isometric torque (MVC) was measured by means of specially designed dynamometers (Vine, Tokyo, Japan) for knee extension and plantar flexion, respectively. All measurements were performed on the right lower limb. Participants had previously visited the laboratory on at least one occasion to become familiarized with the procedures involved. During each task, participants exerted isometric torque from 0 (relax) to MVC within 5 seconds. During the knee extension task, participants sat in an adjustable chair with support for the back and the hip joint flexed at an angle of 80° (full extension = 0°) to standardize the measurements and localize the action to the appropriate muscle group. During torque measurements, the hips and back were held tightly in the seat using adjustable lap belts. The axis of the knee joint was aligned with the axis of the lever arm of the dynamometer. The right ankle was firmly attached to the lever arm of the dynamometer with a strap and fixed with a knee joint flexed at an angle of 90° (full extension = 0°). During the plantar flexion task, participants sat on the chair of a dynamometer with their ankle at 90° (anatomic position) with the knee joint at full extension and the foot securely strapped to a foot plate. Prior to the test, participants performed a standardized warm-up and submaximal contractions to become accustomed to the test procedure. Each task was repeated two or three times per participant with at least 3 minutes between trials. The highest value among these trials was recorded as the muscle strength for each participant.

Elongation and Strain of Tendon Structures

Elongations of the tendon structures in knee extensors and plantar flexors were also assessed during ramp isometric knee extension and plantar flexion. An ultrasonic apparatus (SSD-2000; Aloka) with an electronic linear array probe (7.5-MHz wave frequency with 80 mm scanning length;
UST 5047-5; Aloka) was used to obtain longitudinal ultrasonic images of vastus lateralis and medial gastrocnemius muscles by the procedures described previously (18). The ultrasonic images were recorded on videotape at 30 Hz and were synchronized with recordings of a clock timer for subsequent analyses. The point at which one fascicle was attached to the aponeurosis was visualized on the ultrasonic images. This point moved proximally during isometric torque development up to a maximum [see Figure 1 of (18)]. The displacement of this point indicates the lengthening of the deep aponeurosis and the distal tendon (18). Strain was estimated from the tendon elongation 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 (18,19).

The displacements of tendon and aponeurosis are attributed to both angular rotation and contractile tension, because any angular joint rotation occurs in the direction of knee extension and ankle plantar flexion during an “isometric” contraction (18,19). Thus, angular joint rotation needs to be accounted for to avoid an overestimation of tendon displacement during an isometric contraction. To monitor joint angular rotation, an electrical goniometer (Penny and Giles Biomechanics Ltd., Gwent, U.K.) was placed on the lateral aspect of each joint. To correct the measurements taken for the tendon and aponeurosis elongation, additional measurements were taken under passive conditions. The displacement of each site caused by rotating the knee and ankle from 110° to 70° was digitized in sonographs taken. Thus, for each participant the displacement of each site obtained from the ultrasound images could be corrected for that attributed to joint rotation alone (18). In the present study, only values corrected for angular rotation are reported.

Table 2. Absolute and Relative (to Limb Length) Muscle Thickness of Two Groups, Mean (SD)

<table>
<thead>
<tr>
<th></th>
<th>Young (N = 19)</th>
<th>Elderly (N = 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee extensors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscle thickness, mm</td>
<td>54.3 (5.4)</td>
<td>29.8 (5.3)*</td>
</tr>
<tr>
<td>Muscle thickness/thigh length, mm · cm⁻¹</td>
<td>1.40 (0.14)</td>
<td>0.81 (0.15)*</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscle thickness, mm</td>
<td>74.9 (8.3)</td>
<td>62.7 (6.9)*</td>
</tr>
<tr>
<td>Muscle thickness/thigh length, mm · cm⁻¹</td>
<td>1.91 (0.22)</td>
<td>1.78 (0.19)</td>
</tr>
</tbody>
</table>

Note: *p < .001, significantly different from young.

Statistics

Descriptive data represent means ± standard deviation (SD). One-way analysis of variance (ANOVA) was used for the comparison between the two groups. The level of significance was set at p < .05.

RESULTS

The stature, body mass, and thigh and lower leg lengths of the elderly group were significantly smaller than those of the young group (Table 1). There was no significant difference in the numbers of steps per day between the two groups (p = .617).

Muscle thickness (absolute and relative) of the two groups is presented in Table 2. The elderly group had a significantly lower absolute muscle thickness than the young group in both sites (all p < .001). Relative muscle thickness of the elderly group was significantly lower than that of the young group in knee extensors (p < .001), although no significant difference was found between the two groups in plantar flexors (p = .063). The percentage of the mean value of relative muscle thickness of the elderly group to that of the young group was lower in knee extensors (57.8%) than in plantar flexors (93.2%) (Figure 1).

Muscle strength (absolute and relative) of the two groups is presented in Table 3. The elderly group had significantly lower absolute and relative muscle strength values than the young group in both sites (all p < .001). There was no difference in the relative strength between the two muscle groups of the elderly group compared to the young group (knee extensors = 62.5%, plantar flexors = 65.4%) (Figure 2).

Table 3. Absolute and Relative (to Body Mass) Muscle Strength of Two Groups, Mean (SD)

<table>
<thead>
<tr>
<th></th>
<th>Young (N = 19)</th>
<th>Elderly (N = 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee extensors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscle strength, Nm</td>
<td>216.0 (58.3)</td>
<td>111.7 (34.5)*</td>
</tr>
<tr>
<td>Muscle strength/body mass, Nm · kg⁻¹</td>
<td>3.02 (0.70)</td>
<td>1.89 (0.58)*</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscle strength, Nm</td>
<td>115.8 (25.2)</td>
<td>63.5 (21.1)*</td>
</tr>
<tr>
<td>Muscle strength/body mass, Nm · kg⁻¹</td>
<td>1.62 (0.30)</td>
<td>1.06 (0.30)*</td>
</tr>
</tbody>
</table>

Note: *p < .001, significantly different from young.
The ratio of muscle strength to muscle thickness of the two groups is presented in Figure 3. Although there was no difference in this ratio between the young (3.96 ± 0.89 Nm mm⁻¹) and the elderly (3.88 ± 1.35 Nm mm⁻¹) groups in knee extensors \((p = .831)\), this ratio of the elderly group (1.00 ± 0.28 Nm mm⁻¹) was significantly lower than that of the young group (1.55 ± 0.31 Nm mm⁻¹) \((p < .001)\).

Maximal elongation and strain of tendon structures of the two groups are presented in Table 4. The elderly group had significantly lower maximal elongation and strain of tendon structures in both sites than the young group had. There was no difference in the percentage of the mean value of maximal tendon strain of the elderly group compared to that of the young group between knee extensors (83.8%) and plantar flexors (76.0%) (Figure 4).

**DISCUSSION**

The major findings of this study were that the ratio of muscle strength to muscle thickness of the elderly group was significantly lower than that of the young group in plantar flexors, but not in knee extensors, and that the maximal strain of tendon structures of the elderly group was significantly lower than that of the young group in both sites.

It is well documented that the loss of muscle strength with aging is due to loss of muscle mass [e.g., (4)]. In particular, the knee extensors appear to be affected by muscle atrophy and consequent loss of strength (15,20). In the present study, the percentage values of the mean muscle thickness (58%) and strength (63%) of the elderly group and those of the young group were almost the same (Figures 1 and 2). Accordingly, there was no difference in the ratio of muscle strength to muscle thickness in knee extensors between the young and the elderly groups (Figure 3). Young and coworkers (4) reported that the muscle strength and cross-sectional area of elderly participants were lower by 35% and 33%, respectively, than those of young participants. Furthermore, they showed that there was no difference in the ratio of muscle strength to the cross-sectional area of the quadriceps femoris muscles. Overend and colleagues (3) also demonstrated that the ratio of muscle strength to the cross-sectional area of the quadriceps femoris muscles was similar between young and the elderly men. Thus, the present results of muscle strength to muscle thickness in knee extensors agree with results in previous reports. Some previous researchers showed that there was no difference
between young and elderly groups in the activation level of the quadriceps femoris muscles assessed using twitch interpolation [(21,22)]. Roos and coworkers (22) suggested that the substantial age-related weakness in knee extensors did not seem to be related to changes in neural drive. Taking the present results into account together with the findings quoted above (3,4,21,22), the age-related decline in knee extensor strength can be accounted for by a decrease in muscle mass but not by a decline in the neural activation level.

In plantar flexors, the muscle strength of the elderly group was significantly lower than that of the young group, whereas there was no difference in the relative muscle thickness (to limb length) between the two age groups (Tables 2 and 3). According to a recent finding (15), there was no significant difference in the relative muscle thickness of the medial gastrocnemius muscle between the young and the elderly groups. In the present study, the ratio of muscle strength to muscle thickness in the elderly group was significantly lower than that in the younger group (Figure 3). Some previous studies also demonstrated that, in plantar flexors, the ratio of muscle strength to cross-sectional area of elderly participants was significantly lower than that of young participants (6,7). Furthermore, some previous researchers reported that the activation level (assessed using twitch interpolation) of plantar flexors was significantly lower in elderly participants than in young participants (6,23). These findings suggest that the decrease in plantar flexor strength with aging would be mainly attributed to a decline in the neural activation level of muscles.

However, we must draw attention to a limitation in the present study. The measurement of muscle thickness using ultrasonography cannot distinguish between muscle and intramuscular fat. Some previous studies showed that the amount of intramuscular fat in elderly persons was higher than that in young persons (3,24). Therefore, it is not to be denied that the muscle thickness of the elderly group would be overestimated. In other words, the difference in the age-related ratio of muscle strength to muscle thickness (Figure 3) could be caused by the difference in the quantity of intramuscular fat between knee extensors and plantar flexors. As far as we know, however, there is no definite information on the differences in the amount of intramuscular fat among muscle groups. Regardless, further investigations are needed to clarify this point.

Another interesting finding of this study was that the maximal strain of tendon structures in the elderly group was significantly lower than that in younger participants at both sites. Recently, we observed that the maximal strain of tendon structures in knee extensors decreased significantly with aging (12). In contrast, other studies showed a different finding concerning the age-related changes in the human tendon properties (13,25). For example, Morse and colleagues (13) reported that the human gastrocnemius tendons of elderly persons were more compliant than were those of young adults. At the beginning of the study, therefore, it was expected that the age-related changes in the tendon properties would be different between knee extensors and plantar flexors. In the present study, however, no difference in the percentage of the mean values of maximal tendon strain of elderly participants to that of young participants was found between knee extensors (84%) and plantar flexors (76%) (Figure 4). According to previous findings obtained in in vitro studies using animals and human cadavers (9–11,26,27), the strength and elasticity of tendons, for example, failure load, Young’s modulus, and ultimate strain, decreased with aging. These age-related changes in the mechanical properties of tendons would be caused by morphological and/or mechanical changes in collagen fibers [e.g., (28)]. Previous studies demonstrated that the diameter and crimp angle of collagen fibers decreased with aging (28–31). Furthermore, age-related increases in connective tissue and collagen cross-linking have been reported that might decrease the tendon elasticity during muscle contractions [e.g., (32)]. Considering these previous findings from in vitro studies, it seems reasonable to suppose that the extensibility of the tendon structures decreases with aging.

However, we should present the “stress-strain” relationship to compare the tendon properties of the different age

### Table 4. Maximal Elongation and Strain of Tendon Structures of Two Groups, Mean (SD)

<table>
<thead>
<tr>
<th></th>
<th>Young (N = 19)</th>
<th>Elderly (N = 17)</th>
</tr>
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<tbody>
<tr>
<td>Knee extensors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal elongation, mm</td>
<td>30.7 (6.0)</td>
<td>24.6 (4.7)**</td>
</tr>
<tr>
<td>Maximal strain, %</td>
<td>14.2 (2.8)</td>
<td>11.9 (2.2)*</td>
</tr>
<tr>
<td>Plantar flexors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal elongation, mm</td>
<td>14.2 (3.0)</td>
<td>9.8 (2.7)***</td>
</tr>
<tr>
<td>Maximal strain, %</td>
<td>5.0 (1.3)</td>
<td>3.8 (1.0)***</td>
</tr>
</tbody>
</table>

Note: *p < .05; **p < .01; ***p < .001, significantly different from young.
groups accurately. To achieve this task, we must use some assumptions (e.g., moment arm length, relative contribution of muscles). In the present study, therefore, we used the maximal elongation and strain of tendon structures at MVC as an index of “tendon property.” Therefore, it is possible that the elderly participants have a lower tendon elongation simply because they are weaker than the young participants. In the present study, there was no significant correlation relationship between the relative muscle strength (MVC/body mass) and maximal tendon strain in the knee extensors \((r = 0.294, p > .05)\), although the significant correlation relationship between the two parameters was found in the plantar flexors \((r = 0.582, p < .001)\). In addition, within each age group of the plantar flexors, no significant correlation relationships between the two parameters were found in either young \((r = 0.203, p > .05)\) or elderly \((r = 0.266, p > .05)\) groups. Therefore, we cannot say that the elderly participants have a lower tendon elongation simply because they are weaker than young participants. In the present study, we intended to compare tendon elongation during “voluntary” contraction between the two age groups. Considering these points, it seems reasonable to suppose that the present result (age-related decline in the maximal strain of tendons) would indicate the age-related decline in tendon extensibility during “voluntary” contraction.

In the present study, the number of participants in each age group may have been relatively small. Concerning age-related differences in muscle thickness, however, our previous finding in about 300 men and women showed that the relative muscle thickness (to limb length) of the vastus lateralis muscle was significantly greater in young than in elderly participants, although there were no significant differences in the relative muscle thickness of the medial gastrocnemius muscle between young and elderly participants (15). In addition, the maximal tendon strain of elderly participants was lower than that of young participants according to our previous findings in 51 women (12). Therefore, the present results agreed with these previous findings (12,15). However, these conclusions are speculative and await additional data for clarification.

Conclusion

Our results indicated that the age-related weakening of knee extensors may be attributed to muscle atrophy, whereas in plantar flexors it may be related to a decline in the neural activation level. Furthermore, elderly persons have less extensible tendon structures in knee extensors and plantar flexors compared to young persons. According to the present results, it is desirable that the main aims of an exercise program for elderly individuals are increases in the muscle volume of knee extensors and the neural activation of plantar flexors. In addition, we should note that tendon structures in elderly persons are less able to cope with repetitive biomechanical stress due to a decrease in tendon extensibility.

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