Elasticity of tendon structures of the lower limbs in sprinters

K. KUBO, H. KANEHISA, Y. KAWAKAMI and T. FUKUNAGA
Department of Life Sciences (Sports Sciences), University of Tokyo, Komaba, Meguro-ku, Tokyo, Japan

ABSTRACT
The present study aims to investigate the elasticity of tendon structures of the lower limbs in sprinters and its relation with sprint performance. Subjects were 10 male sprinters and 14 controls whose anthropometric variables and isometric maximum strength were similar. The elongation ($L_o$) of the tendon and aponeurosis of vastus lateralis (VL) and medial gastrocnemius muscles (MG) during isometric knee extension and plantar flexion, respectively, were determined using a real-time ultrasonic apparatus in vivo, while the subjects developed a gradually increasing torque from zero (relax) to maximal effort (MVC) within 5 s. While sprinters compared with controls showed significantly greater $L_o$ above 500 N (about 50% of MVC) and higher $dL/dF$ for VL at less than 20% of MVC during knee extension, there were no significant differences between the two groups in $L_o$ and $dL/dF$ for MG at every 10% of MVC during plantar flexion. Moreover, the average value of $dL/dF$ above 50% of MVC, proposed as the compliance of tendon structures, did not significantly differ between sprinters and controls in either VL or MG. In a regression analysis within sprinters, the compliance of VL was negatively correlated to 100-m sprint time, $r^2 = 0.757$ ($P < 0.05$), but that of MG was not, $r = 0.228$ ($P > 0.05$). Thus the present results indicate that the elasticity of tendon structures of VL and MG at high force production levels, which might be assumed to associate with the storage and subsequent release of energy during exercises involving the stretch-shortening cycle, are similar in both sprinters and controls. For sprinters, however, the tendon structures of VL are more compliant than that for controls at low force production levels, and its elasticity at high force production levels may influence sprint performance.

Keywords compliance, medial gastrocnemius, performance, sprint, ultrasonography, vastus lateralis.

A training program for an athlete is designed so as to increase the physiological capacity appropriate to the specific demand in his chosen sport (Fox 1979). The training regimen for sprinters mainly consists of sprint running and additional high intensity exercises such as resistance training or jumping. Although a great deal of attention has been paid to the effects of these high intensity exercises on the morphological, biochemical and/or histochemical profiles of muscles, little is known about the changes which may be produced in the mechanical properties of tendon structures in humans. Sprint running induces stretch-shortening cycles (SSCs) in the muscle–tendon complex (MTC) in the lower limbs, in which lengthening and shortening actions of MTC are repeated. In exercises involving SSC such as running or jumping, it is known that elastic energy is stored in tendon structures at the lengthening phase and is reused at the shortening phase (Cavagna 1977). Cook & McDonagh (1995) have shown that the total compliance of human MTC has important effects on the mechanics of eccentric muscle actions. Also, a study using animal muscle has indicated that the compliance of MTC makes a large contribution to the performance of SSC activities (Ettema et al. 1992). These findings lead us to hypothesize that, as a result of long-term participation in sprint training, the tendon structures of the lower limbs in sprinters are more compliant which facilitates the storage and/or reuse of elastic energy as compared with untrained persons, and this influences sprint performance.

It is well known that a muscle changes the morphological and functional aspects in accordance with the extent of use and disuse during daily life. Similarly, the elasticity of MTC changes through

Correspondence: Tetsuo Fukunaga PhD, Department of Life Sciences (Sports Sciences), University of Tokyo, Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan.
training, although how it adapts to exercise differs between training modes performed (Pousson et al. 1990, 1991, Wilson et al. 1992). For example, Pousson et al. (1991) observed a decrease in the stiffness of rat soleus muscle after 11-week vertical jumping training. Moreover, Wilson et al. (1992) reported that 8-week flexibility training of power lifters induced a significant reduction in the maximal MTC stiffness of the upper body musculature. Pousson et al. (1990), however, found that 6-week eccentric training increased the MTC stiffness in human elbow flexors. However, the above-quoted findings do not distinguish between adaptations of different tissues such as the connective tissue, sarcomere and the contractile tissue (Wilson et al. 1992). To our knowledge, no studies have ever tried to investigate the effects of training on the mechanical profiles of human tendons in vivo.

It had so far been impossible to measure directly the elasticity of tendon structures in humans in vivo. Recently, Cook & McDonagh (1996) tried to determine the stiffness of MTC in human first dorsal interosseous muscle by imposing a small fast stretch to muscles stimulated tetanically. In their study, an adaptation of the method of Morgan (1977) allowed the stiffness to be separated into two components: the stiffness of muscle fibres and the stiffness of tendon. Moreover, improvements in imaging techniques such as MRI and real-time ultrasonography made it possible to determine the architectural profiles of human MTC in vivo (Narici et al. 1992, Fukashiro et al. 1995, Fukunaga et al. 1997, Ito et al. 1998). Among the previous studies using these techniques, Fukashiro et al. (1995) reported that the mechanical properties of tendon structures in humans could be determined in vivo by the use of a real-time ultrasonography for measuring the magnitude of the lengthening of tendon and aponeurosis during isometric contractions. Similarly, Ito et al. (1998) showed that ultrasonography was useful for measuring the stiffness and Young’s modulus of human tendons in vivo.

In the present study, a real-time ultrasonic apparatus was adopted for sprinters and untrained subjects to determine the elongation of the tendon and aponeurosis of the vastus lateralis and medial gastrocnemius muscles during isometric knee extension and plantar flexion, respectively. The purpose of this study is to investigate the elasticity of tendon structures of the lower limbs in sprinters and its relation to sprint performance.

METHODS

Subjects

Ten sprinters voluntarily participated in the present study as subjects. The duration of training experience in sprint running for sprinters ranged from 4.8 to 10.0 years (6.7 ± 2.2 years, mean ± SD). All the subjects of sprinters had participated in competitive meets at the regional or inter-college level within the preceding year, and their best official record in the 100-m race was from 10.70 to 11.26 s (11.01 ± 0.17 s). In a preliminary study, 14 untrained subjects whose anthropometric variables and isometric maximum knee extension and plantar flexion torque were similar to those of sprinters were selected as a control group. The physical characteristics of the subjects are summarized in Table 1. All controls were either sedentary or mildly active but none had been involved in any type of regular exercise program for at least 1 year prior to the test. This study was approved by the office of the Department of Sports Sciences, University of Tokyo and was consistent with their requirements for human experimentation. The subjects were fully informed of the procedures to be utilized as well as the purpose of the study. Written informed consent was obtained from all the subjects.

### Measurement of force

A dynamometer (Cybex 7200) was used to determine torque output during isometric knee extension and plantar flexion. Prior to the test, the dynamometer system was calibrated using weights on the lever arm. For both the actions, the subject was instructed to develop a gradually increasing force from relax to maximal voluntary contraction (MVC) within 5 s. In the case of the knee extension task, the subjects sat in an adjustable chair with support for the back and hips 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 80° (full extension = 0°). During the plantar flexion task, the subject lay prone on a test bench and the ankle and shoulders were secured by adjustable lap belts and held in position. The right ankle joint was set at 90° (anatomical position) with the knee joint at full extension.

### Table 1 Physical characteristics of subjects (mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Sprinters (n = 10)</th>
<th>Controls (n = 14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>21.4 ± 1.8</td>
<td>24.6 ± 2.2</td>
</tr>
<tr>
<td>Body height (cm)</td>
<td>171.2 ± 5.6</td>
<td>170.8 ± 6.4</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>68.6 ± 7.2</td>
<td>72.2 ± 7.9</td>
</tr>
<tr>
<td>Thigh length (cm)</td>
<td>39.6 ± 1.4</td>
<td>38.6 ± 1.3</td>
</tr>
<tr>
<td>Lower leg length (cm)</td>
<td>39.3 ± 1.2</td>
<td>38.5 ± 1.6</td>
</tr>
</tbody>
</table>

© 2000 Scandinavian Physiological Society
and the foot was securely strapped to a foot plate connected to the lever arm of the dynamometer. The knee extension and plantar flexion tasks were performed on separate days. The order of the execution of the two experimental conditions was random for each subject. Prior to the test, the subject performed a standardized warm-up and submaximal contractions to be accustomed to the test procedure. Each of the knee extension and plantar flexion tasks was repeated two or three times per subject with at least 3 min between trials. Torque signals were A/D converted at a sampling rate of 1 kHz (MacLab/8, type ML780, AD Instrument, Japan) and analysed by a personal computer (Performa 630, Macintosh, Japan). The measured values that are shown below are the means of two trials.

The measured torque during isometric knee extension and plantar flexion were converted to force unit ($F$) by the following equations:

$$F = k \times T \times M^{-1}$$

where $k$ is the relative contribution of the physiological cross-sectional area in each of the vastus lateralis muscle (VL) within quadriceps femoris muscles (22%, Narici et al. 1992) and medial gastrocnemius muscle (MG) within plantar flexor muscles (18%, Fukunaga et al. 1996), $T$ is the measured torque and $M$ is the moment arm length in each of the quadriceps femoris muscles at 80° (43 mm, Smidt 1973) and triceps surae muscles at 90° (50 mm, Rugg et al. 1990).

Measurement of the elongation of tendon structures

A real-time ultrasonic apparatus (SSD-2000, Aloka, Japan) was used to obtain longitudinal ultrasonic images of the VL and MG in the right leg by the procedures described by Fukunaga et al. (1997) and Kawakami et al. (1998), respectively. Two sites were selected for measurements: at 50% of the distance between the greater trochanter and the lateral epicondyle of the femur for VL and at 30% of the distance between the popliteal crease and the centre of the lateral malleolus for MG. At these levels, the widths of VL and MG were visualized by use of the ultrasound apparatus, and the position of one-half of the width was marked with pen. At this position, longitudinal images were obtained. The precision and linearity of the images for VL and MG have been confirmed by prior studies (Fukunaga et al. 1997, Kawakami et al. 1998). During the measurements, the ultrasonic images were recorded on video tape at 30 Hz, synchronized with recordings of a clock timer, and then printed every 33 ms onto calibrated recording film (SSZ-305, Aloka, Japan). Figure 1 shows typical recordings of ultrasonic images of VL during knee extension at 0, 50 and 100% of MVC. In each of the longitudinal images, the cross-point ($P$) of two echoes from the deep aponeurosis and fascicles moved proximally with the increasing force production level. A marker ($X$) which was placed between the skin and the probe and the cross-point which was identified between the superficial aponeurosis and fascicle did not show any evidence of shifting during the measurements. Hence the displacement of $P$ was considered as the lengthening of the deep aponeurosis and the distal tendon as described by Fukashiro et al. (1995) and Ito et al. (1998). The distance which $P$ moved was determined as the lengthening ($L$) of tendon structures during isometric contractions.

**Figure 1** Ultrasonic images of longitudinal sections of vastus lateralis muscle during isometric contractions at 0, 50 and 100% of MVC. The cross-point ($P$) of two echoes from the deep aponeurosis and fascicles moved proximally with the increasing force production level. A marker ($X$) which was placed between the skin and the probe did not show any evidence of shifting during the measurements. The displacement of $P$ was defined as the lengthening of the deep aponeurosis and the distal tendon.
Calculation of the elasticity

Elasticity is a function of force generation and length changes and is usually measured as stiffness (force generation/length change) or as its reciprocal, compliance (Cook & McDonagh 1996). In the present study, firstly the relationship between F and L was certified and then the ratio of the change in L (dL) to that in F (dF) at 10% of MVC, dL/dF, was proposed to assess the force–compliance relation. Figure 2a presents a typical example of the relationship between F and L in VL. As reported in previous studies using animal and human cadaver tendons in vitro (e.g. Benedict et al. 1968, Woo et al. 1981), the relation between F and L was curvilinear consisting of an initial region (toe-region) characterized by a large increase in L with increasing force and a linear region immediately after the toe-region. And so, the dL/dF at every 10% of MVC decreased with increasing force production levels from 10% to 40–50% of MVC, and became almost constant in the range 50–100% of MVC (Fig. 2b). In view of the literature concerning the mechanical properties of tendons, the ratio of the change in load to that of elongation of tendon in the linear region has been calculated as an estimate of tendon stiffness (Viidik 1986). In addition to dL/dF at every 10% of MVC therefore we proposed the average value of dL/dF at above 50% of MVC as the compliance of tendon structures. The intra-class correlation coefficient for the test–retest of compliance measurement was 0.89 for VL and 0.91 for MG and the coefficients of repeatability (Brand & Altman 1986) were 0.07 × 10⁻² mm N⁻¹ for VL and 0.15 × 10⁻² mm N⁻¹ for MG.

Statistics

Descriptive data included mean ± SD. The linear correlation coefficient (r) was calculated using the method of least squares. A one-way analysis of variance (ANOVA) was used to detect the significant effect of force level (%MVC) on the dL/dF at every 10% of MVC. In the event of a significant F-value in ANOVA, Tukey’s post hoc test on critical difference was used to locate the significance difference between means. The significance of the difference between sprinters and controls in the descriptive data was analysed by the use of Student’s t-test. The level of significance was set at a P-value of less than 0.05.

RESULTS

There were no significant differences between sprinters and controls in MVC during knee extension and flexion; 241.9 ± 27.5 N m in sprinters vs. 234.0 ± 38.9 N m in controls for knee extension and 131.6 ± 34.2 N m in sprinters vs. 133.4 ± 31.0 N m in controls for plantar flexion.

Figure 3 shows the relationships between F and L in VL and MG. In the case of VL, the extent of elongation in sprinters tended to be greater than that in controls. The differences between the two groups were statistically significant at force development above 500 N (about 50% of MVC). The maximum elongation (Lmax) at MVC for VL was significantly greater in sprinters (41.3 ± 2.6 mm) than in controls (33.3 ± 4.2 mm). In the case of MG, however, there were no significant differences in L between sprinters and controls at any force production level, and the Lmax of MG was similar.
in both the groups; 23.7 ± 3.0 mm in sprinters and 24.7 ± 4.8 mm in controls.

Figure 4 indicates the relation between %MVC and dL/dF in VL and MG. In both muscles, the dL/dF at every 10% of MVC decreased with increasing force production levels from 10 to 40–50% of MVC, and became almost constant in the range 50–100% of MVC. For VL, the dL/dF values at 10 and 20% of MVC were significantly higher in sprinters than in controls. However, MG did not differ significantly between sprinters and controls in dL/dF at any force level. In both VL and MG, there were no significant differences between sprinters and controls in the compliance values; 1.91 ± 0.38 × 10⁻² mm N⁻¹ in sprinters vs. 1.83 ± 0.31 × 10⁻² mm N⁻¹ in controls for VL and 4.53 ± 0.83 × 10⁻² mm N⁻¹ in sprinters vs. 4.12 ± 1.35 × 10⁻² mm N⁻¹ in controls for MG.

Figure 5 shows the relation between the compliance of VL and 100-m sprint time for sprinters. The compliance of VL was negatively correlated to the 100-m sprint time, r = −0.757 (P < 0.05), but that of MG was not, r = 0.228 (P > 0.05).

DISCUSSION

Before interpreting the present results, mention should be made of the functional significance of the compliance proposed in the present study. The compliance was the average value of dL/dF at above 50% of MVC.
of which the $F-L$ relation became linear. The shape of the load–elongation curve varies for different tendons, but a toe-region is always found in which the compliance of the tendon is the highest (Ker 1981). The toe-region is generated by crimping of the collagen fibres (Diament et al. 1972). The energy storage capacity of the tendon is not primarily due to the straightening out of the crimp, but to the elastic properties of the straightened collagen fibres (Ker 1981). Hence, we may say that the compliance proposed in the present study indicates the capacity of the tendon, which will be responsible for the storage by lengthening and subsequent release of energy by shortening (Alexander 1984, Griffiths 1989).

Given the above-mentioned points, the present result that no significant differences in the compliance of VL and MG were found between sprinters and controls negates the hypothesis built up at the beginning of the study, and suggests no significant effect of sprint training on the elasticity of the tendon structures of the lower limbs, assumed to be responsible for the storage and release of elastic energy at high levels of contraction. This somewhat differs from previous findings which indicate that the elasticity of human MTC is changeable through training (Pousson et al. 1990, 1991, Wilson et al. 1992). However, because the changes induced by training in the elasticity of MTC would involve adaptations of different tissues such as the connective tissue, sarcomere and the contractile tissue (Wilson et al. 1992), they cannot be used to interpret the present result on the compliance which represents the elasticity of the tendon structure itself. With regard to the effects of training on human connective tissue itself, few comparisons have been made between data obtained from athletes and untrained persons by biochemical and/or morphological approaches. It was reported that the proportion of collagen in the biceps (MacDougall et al. 1984) and the cross-sectional area of the Achilles tendon (Nakagawa et al. 1989) were similar in strength-trained athletes and untrained persons.

Previous studies using bone–ligament or bone–tendon preparations of animals have provided evidence that the morphological and mechanical properties of connective tissues are also changeable through training and immobilization (Booth & Gould 1975, Butler et al. 1978, Viidik 1986, Stone 1988). In these studies, the mechanical properties of connective tissues have been evaluated on the basis of stress–strain curves. The parameters usually proposed involve the ultimate tensile strength and the strain at that point, the inclination of the linear part of the stress–strain curve, elastic stiffness and failure energy calculated as the area between the curve and the strain axis (Viidik 1986). Among these parameters, the ultimate tensile strength of the bone–ligament or bone–tendon preparations increases as a result of endurance training (Stone 1988), but not sprint training (Tipton et al. 1975). Simonesen et al. (1995) also reported that strength training produced no significant changes in the ultimate tensile strength of the rat Achilles tendon. On the other hand, no consensus on whether the changes in the elastic properties of connective tissues depend on exercise modes has been reached. For example, Viidik (1986) failed to find a significant change in the stiffness of the anterior cruciate ligament of rabbits following endurance training. In the report of Tipton et al. (1975), too, no significant changes were found in the stiffness of ligament–bone junctions after either endurance or sprint training. However, Woo et al. (1981) observed that the stiffness of swine tendon was significantly increased by endurance training. These discrepancies can be partially explained by species and/or specimen type differences (Viidik 1986). However, the studies using animals have been criticized as simply being reverse immobilization research when the trained animals are compared with caged animals (Stone 1988). In fact, Tipton et al. (1975) showed evidence that the bone–tibial junction of dogs maintained in pens showed a higher ratio of tensile strength to body weight than that of caged and exercised dogs. From the findings of Shadwich (1990) who investigated the mechanical properties of the digital flexor and extensor tendons of pigs in relation to age, it is clear that these tendons become much stronger, stiffer, less extensible, and more resilient with growth and ageing. However, these alterations in elastic properties occur to a significantly greater degree in the high-load-bearing
flexors than in the low-stress extensors. Furthermore, Woo et al. (1982) demonstrated that, as a result of endurance training in swine, initially stiffer digital flexor tendons did not increase their stiffness, while the less stiff digital extensor tendons did become as stiff as the flexor tendons after training. Both VL and MG act for body mass bearing in physical activities during daily life. Taking this point into account together with the above-quoted findings, it is likely that the tendon components of these muscles do not modify easily their elasticities by training beyond the level achieved by physical activities during daily life. The similarity observed in the compliance between sprinters and controls is consistent with this proposed explanation.

An interesting finding in the present study is that \( \frac{dL}{dF} \) at less than 20% of MVC for VL was significantly higher in sprinters than in controls, and consequently it induced significantly greater elongation of VL at above 50% of MVC in sprinters compared with controls. As described earlier in this paper, the elongation of tendon at low levels of contraction is owing to the crimping of the collagen fibres, and its compliance is high at this point (Rigby et al. 1959). Danielsen & Andereassen (1988) reported that the variability of the mechanical quality of collagen originates from differences in either the cross-link pattern of the collagen or structure and packing of the collagen fibres. Hence, the higher \( \frac{dL}{dF} \) of VL at less than 20% of MVC in sprinters tempts us to speculate that the arrangements of collagen fibres in the tendon component of VL for sprinters may differ from those for controls. Even if this is so, the mechanisms which resulted in the difference are unknown but the higher \( \frac{dL}{dF} \) of VL at low levels of activation and longer elongation at above 50% of MVC may play to reduce the risk of knee injury with the execution of sprint running. Namely, there is general agreement that the knee is the single most frequently reported site of pain requiring medical attention or interfering with daily life. Taking this point into account together with the findings of Wilson et al. (1991, 1992) who attempted to investigate the influences of MTC stiffness on the performance of SSC activities. They observed that the benefit derived from the prior stretch of muscle during a bench press lift was negatively correlated to the maximal stiffness of MTC involved in the lift, and observed an increase of the bench press performance with a reduction in the maximal MTC stiffness after flexibility training. It has been documented that a compliant MTC will increase the contribution of elastic strain energy to SSC activities (Cavagna 1977, Shorten 1987). In addition, kinetic and dynamometric analyses have provided data which suggest an important role for compliant tendon in controlling the shortening velocity of muscle fibres during SSC activities (van Ingen Schenau et al. 1985, Bobbert et al. 1986). For example, Bobbert et al. (1986) indicated that, if the tendon was not compliant, triceps surae muscle would not be able to satisfy a high angular velocity with a large moment during plantar flexion in jumping. With regard to this point, Proske & Morgan (1987) have reviewed the role of compliant tendon during muscle contractions. They suggested that a significant amount of shortening can be taken up by recoil of a previously stretched tendon when MTC is shortened during a phase of movement where the overall level of tension is falling, and this induces an increase in the level of load a muscle can bear by the effective shortening speed of muscle fibres as a result of the force–velocity relation. This would reason why a knee joint moment of nearly 200 N m can be developed at high angular velocities (>10 rad s\(^{-1}\)) during maximal sprinting (Ae et al. 1985) in spite of the evidence that isolated knee extensor muscles do not have the force generation capacity to develop such a moment at that velocity (Wickiewicz et al. 1984). Given these points, it is reasonable to assume that the more compliant tendon structures of the knee extensor muscles in sprinters help to develop the higher force at the stance phase in which the foot contacts the ground, and consequently are a factor in the negative correlation between compliance and sprint time.

In the stance phase during running, the resultant joint moment is initially eccentric and helps to absorb the shock of landing and control the forward rotation of the tibia over the ankle, and then concentric as it aids in propulsion (Putnam & Kozy 1989). Devita et al. (1992), who investigated the effect of landing stiffness on joint kinetics and energetics in the lower extremity, reported that the ankle plantar flexor provided the major energy absorption function in both soft and stiff landings from a vertical fall of 59 cm. In the study of Ae et al. (1985), the positive work done by the plantar flexors was highly correlated with stride length and stride frequency.
Therefore, it was expected that the elastic properties of MG in sprinters would be different from those in controls, and correlated to sprint performance. However, the $dL/dF$ at every 10% of MVC and compliance of MG were similar between the two groups, and the compliance was not significantly correlated to sprint time. The reasons for the discrepancy are unknown. On the other hand, a stiff tendon would be advantageous for performing brisk, accurate movements because it affects rapid tension changes (Proske & Morgan 1987). Hence, the present result that the MG of sprinters was not so compliant might match with the characteristics of competitive activities in sprint running. Alternatively, taking the muscle and tendon components in the lower extremity together with the mass they support as a resonant system, it seems that the optimal elasticity that allows a match with that of VL exists in MG for performing sprint running effectively. If so, the similarity between sprinters and controls in the measured elastic parameters for MG might be interpreted as a concomitant consequence of the higher $dL/dF$ at less than 20% of MVC and longer $L$ at above 50% of MVC in sprinters. In any case, further investigations are needed to clear up this point.

In summary, the present results indicate that the elasticity of tendon structures of vastus lateralis and medial gastrocnemius muscles at high force production levels, which might be assumed to associate with the storage and subsequent release of energy during exercises involving the stretch-shortening cycle, are similar in both sprinters and untrained persons. For sprinters, however, the tendon component of vastus lateralis is more compliant at low force production levels, and its elasticity at high force production levels may influence sprint performance.

REFERENCES


