

# ***In vivo* dynamics of human medial gastrocnemius muscle-tendon complex during stretch-shortening cycle exercise**

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## **ABSTRACT**

The purpose of this study was to investigate the dynamics of human muscle-tendon complex (MTC) during stretch-shortening cycle exercises through *in vivo* observation. A total of seven male subjects performed dorsi flexion followed by plantar flexion at two different frequencies, 0.3 Hz (slow) and 1.0 Hz (fast), in a toe-standing position. The fascicle length ( $L_F$ ) of the medial gastrocnemius muscle during the movements was determined using a real-time ultrasonography *in vivo*. The  $L_F$  at the switching phase from dorsi to plantar flexion was significantly shorter in the fast exercise ( $54.4 \pm 5.5$  mm) than in the slow one ( $58.2 \pm 5.4$  mm), suggesting that the elongation of tendon structures at that time was significantly greater in the former than in the latter. Furthermore, at the initial stage of plantar flexion during the fast movement, the  $L_F$  hardly changed with a rapid shortening of tendon structures at that time. The observed relation between MTC length and force showed that the behaviour of tendon structures contributed to 20.2 and 42.5% of the total amount of work completed during plantar flexion phase in the slow and fast movements, respectively. Thus, the present results suggest that tendon structures make the dynamics of MTC more efficient during stretch-shortening cycle exercises by changing their lengths.

**Keywords** fascicle length, medial gastrocnemius muscle, plantar flexion, tendon structures, ultrasonography.

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The stretch-shortening cycle can be defined as a combination of eccentric and concentric muscle actions. Activities like walking, running, jumping and throwing meet the criteria for the stretch-shortening cycle in which an eccentric action is immediately followed by a concentric action of working muscles. The enhanced performance of the concentric action in a stretch-shortening cycle compared with a pure concentric action only has been well documented (e.g. Cavagna 1977) and attributed to the combined effects of utilization of elastic energy and stretch reflex potentiation in the exercising muscles (Bosco *et al.* 1982).

Previous studies have investigated physiological backgrounds for the enhanced performances in the stretch-shortening cycle exercises on the basis of measured variables such as joint angle, ground reaction force, electromyogram and/or oxygen requirement

(Komi & Bosco 1978, Belli & Bosco 1992). Further, other researches have tried to demonstrate the dynamics of muscle-tendon complex (MTC) in the stretch-shortening cycle exercises through modelling and/or simulation approaches (Hof *et al.* 1983, Bobbert *et al.* 1986, Anderson & Pandy 1993, Voigt *et al.* 1995). However, the behaviour of human skeletal muscles during stretch-shortening cycle exercises has not been determined directly *in vivo*, and so the precise mechanisms remain to be clarified.

Recently, a real-time ultrasonography enabled *in vivo* muscle scanning and promised a realistic determination of changes in muscle architecture during exercises (e.g. Narici *et al.* 1996, Ichinose *et al.* 1997). Narici *et al.* (1996) and Ichinose *et al.* (1997), who studied on the human medial gastrocnemius and vastus lateralis muscles, respectively, reported the shortening of muscle fibres (about 30%) during 'isometric'

contractions *in vivo*. From experiments in animals, the changes in muscle fibre length do not necessarily correspond with those in joint angle (Hoffer *et al.* 1989, Griffiths 1991). For example, Hoffer *et al.* (1989) demonstrated that lengthening and shortening happened simultaneously during locomotion in cat Achilles tendon and medial gastrocnemius muscle, respectively. These findings suggest that the interaction between length changes of muscle fibres and tendon structures should be considered when discussing the dynamics of MTC during movement in humans.

In the present study, the fascicle lengths during stretch-shortening cycle exercises were determined using a real time ultrasonography. The purpose of this study was to investigate the behaviour of fascicles and tendon structures during stretch-shortening cycle exercises in human *in vivo*.

## METHODS

### Subjects

A total number of seven healthy males ( $24.7 \pm 1.6$  years,  $168.6 \pm 2.8$  cm,  $68.5 \pm 9.8$  kg; mean  $\pm$  SD) voluntarily participated in the study. All subjects were physically active, but had not previously taken part in regular exercise programmes. 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. All subjects were fully informed of the procedures to be used as well as the purpose of the study. Written informed consent was obtained from all the subjects.

### Exercise protocols

Subjects lowered their heels (dorsi-flexion) from a toe-standing position (ankle joint angle =  $120^\circ$ ) and immediately raised them (plantar flexion) back to a toe-standing position at two different frequencies, 0.3 Hz (slow) and 1.0 Hz (fast). The tasks were performed on a force platform (Kistler, 9281B, Switzerland). In the slow exercise, the vertical component of the ground reaction force averaged 1.01 times the body weight with a small variation of 0.93–1.05. For the fast exercise, the vertical reaction force was about 1.50 (1.43–1.57) times body weight at the changing phase from dorsi to plantar flexion (ankle joint angle,  $90^\circ$ ). To ensure that the performances were executed by the calf muscle only, knee and hip joints were fixed with orthopaedic casts. After the subject familiarized himself with the testing procedures, he performed the two tasks with a 1 min rest between the trials. The descriptive data presented in the text were the mean values for the two trials.

### Fascicle length and angle

A real-time ultrasonic apparatus (SSD-2000, Aloka, Japan) was used to record continuously longitudinal ultrasonic images of the medial gastrocnemius muscle during the exercises (Fig. 1). At 70% of the distance from the centre of the malleolus lateralis to the articular cleft between the femur and tibia condyles, the scanning probe (7.5 MHz) of the apparatus was secured with adhesive tape on the skin. The ultrasonic images were recorded on a video tape at 30 Hz, synchronized with recordings of a clock timer for subsequent analysis. The fascicle length ( $L_F$ ) was defined as the distance between the insertions of the fascicle into the superficial and deep aponeurosis. The fascicle angle ( $A_F$ ) was defined as the angle between the fascicle and deep aponeurosis. Measurements of  $L_F$  and  $A_F$  were performed five times for the same image using a dedicated software (DIG-98, DITECT, Japan). The average value of the three measurements excluding the largest and the smallest values was proposed and used as a representative score at a given ankle-joint angle. The coefficients of variation of three measurements ranged from 0 to 3.8% (mean: 1.7%) for  $L_F$  and 0–4.5% (mean: 2.0%) for  $A_F$ . Also, the coefficients of variation of the two exercise trials ranged from 0.2 to 6.2% (mean: 2.9%) for  $L_F$  and 0.4–5.4% (mean: 2.6%) for  $A_F$ .

In accordance with the technique of Cavagna (1970) and Belli & Bosco (1992), the medial gastrocnemius muscle was modelled with two basic mechanical components (Fig. 2); the fascicle as a contractile component and the tendon structures as a series elastic component. The length of MTC ( $L_{MTC}$ ) was calculated using the equations of Greive *et al.* (1978):

$$L_{MTC} = L_L \cdot (-15.72217 + 0.30141 \cdot A_J - 0.00061 \cdot A_J^2)$$

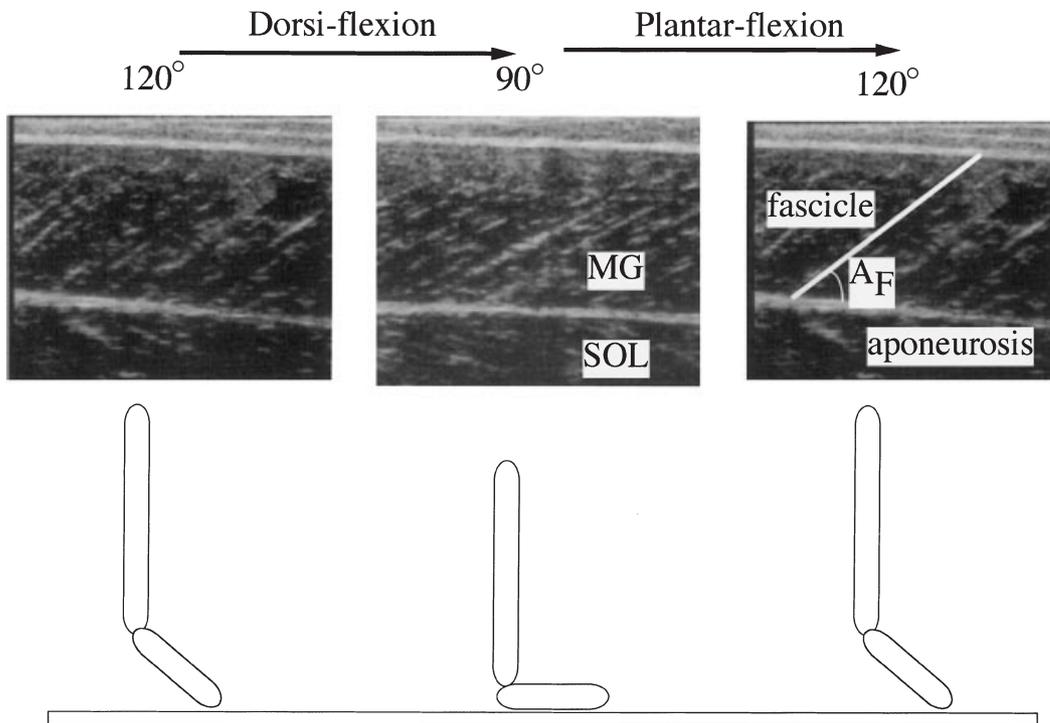
where  $A_J$  and  $L_L$  are the ankle-joint angle and the lower-leg length (i.e. the distance from the centre of the malleolus lateralis to the articular cleft between the femur and tibia condyles), respectively. Also, the length of the tendon structures ( $L_T$ ) was calculated with the following equations:

$$\begin{aligned} L_T &= L_{T1} + L_{T2} \\ &= L_{MTC} - L_F - \cos A_F^{-1} \end{aligned}$$

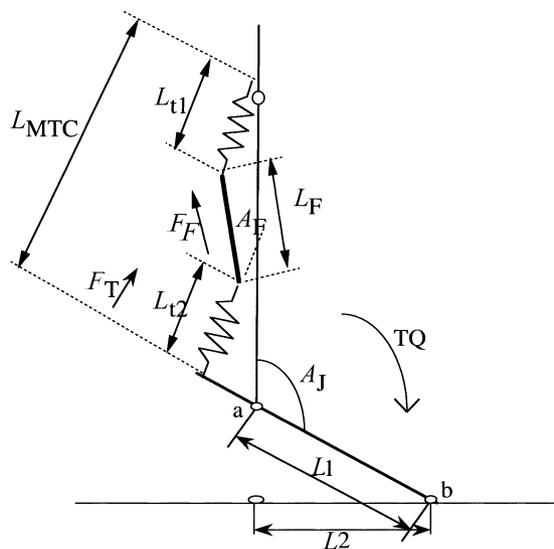
where  $L_{T1}$  and  $L_{T2}$  are the length of proximal and distal tendon structures, respectively.

### Electromyogram

Electromyographic (EMG) activity was recorded from the medial gastrocnemius muscle. Bipolar surface electrodes (5 mm in diameter) were placed over the bellies of medial gastrocnemius muscle with a constant



**Figure 1** Ultrasonic images of longitudinal sections of medial gastrocnemius muscle obtained during exercises. In the images the pennation of fascicle is identifiable as the diagonal striations running across the muscle from the deep to the superficial aponeurosis.



**Figure 2** Schematic representation of the mechanical model used for the ankle and the medial gastrocnemius muscle.  $L_F$ ,  $L_{MTC}$ ,  $L_{T1}$  and  $L_{T2}$  are  $L_F$ , MTC, proximal tendon structures and distal tendon structures, respectively.  $F_F$  and  $F_T$  are the force of fascicle and tendon structures, respectively.  $A_F$  and  $A_J$  are the angle of fascicle and ankle joint, respectively.

interelectrode distance of 25 mm. The EMG signals were amplified and the full-wave rectified. The rectified EMG signals were integrated with respect to time every

$2^\circ$  on the  $A_J$ , and the obtained integrated EMG were averaged for every  $2^\circ$  on the  $A_J$  (mEMG).

*Kinetic and kinematic analysis*

The  $A_J$  was recorded with an electrogoniometer attached to the right-ankle joint, and the vertical component of the ground reaction force ( $F_z$ ) was recorded from the force platform. The  $A_J$  and  $F_z$  signals were A/D converted at a sampling rate of 1 kHz (MacLab/8, type ML780, AD Instrument, Tokyo, Japan) and analysed by a computer (Macintosh Performa 630, Apple, Cupertino, USA). The ankle joint torque (TQ) was calculated from the following equation:

$$TQ = (1/2 \cdot F_z) \cdot \{L1 \cdot \cos(A_J - 90)\}$$

where  $L1$  is the length from the retromalleolaris medialis (a) to the action point (b). It was assumed that both legs bore equally the body weight, and that the action point (b) did not move (Fig. 2).

In a preliminary study using three male subjects, we examined the validity of the simple model for calculating TQ comparing with data obtained using standard inverse dynamics as described by Winter (1990). As a result, the centre of pressure (action point; b) moved backward  $10.2 \pm 2.1$  mm at the changing phase from dorsi to plantar flexion. Consequently, the peak value in the torque curve obtained by the simple model used in

the present study was 10.4% higher than that obtained by standard inverse dynamics. However, the pattern of torque development during exercise was similar between the two calculations. These observations agreed with the finding of McCaw & DeVita (1995). In the present study, we aimed to investigate the interaction between muscle fibres and tendon structures during exercises at two different speeds. For this purpose, we considered the simple model to be sufficiently accurate.

The fascicle force ( $F_F$ ) was calculated from the following equation:

$$F_T = \kappa \cdot TQ \cdot MA^{-1}$$

$$F_F = F_T \cdot \cos A_F^{-1}$$

where  $F_T$  and  $\kappa$  represent the medial gastrocnemius-tendon force and the relative contribution of medial gastrocnemius muscle to the triceps surae muscles in terms of physiological cross-sectional area (18%, Fukunaga *et al.* 1996), respectively, and  $MA$  is the moment arm length of medial gastrocnemius muscle at the anatomical position (50 mm, Rugg *et al.* 1990).

The mechanical work carried out by each of MTC, fascicle and tendon structures were calculated as the area below the curves of  $F_T-L_{MTC}$ ,  $F_F-L_F$  and  $F_T-L_T$  relations, respectively. The mechanical works during dorsi and plantar flexion were defined as negative and positive work, respectively.

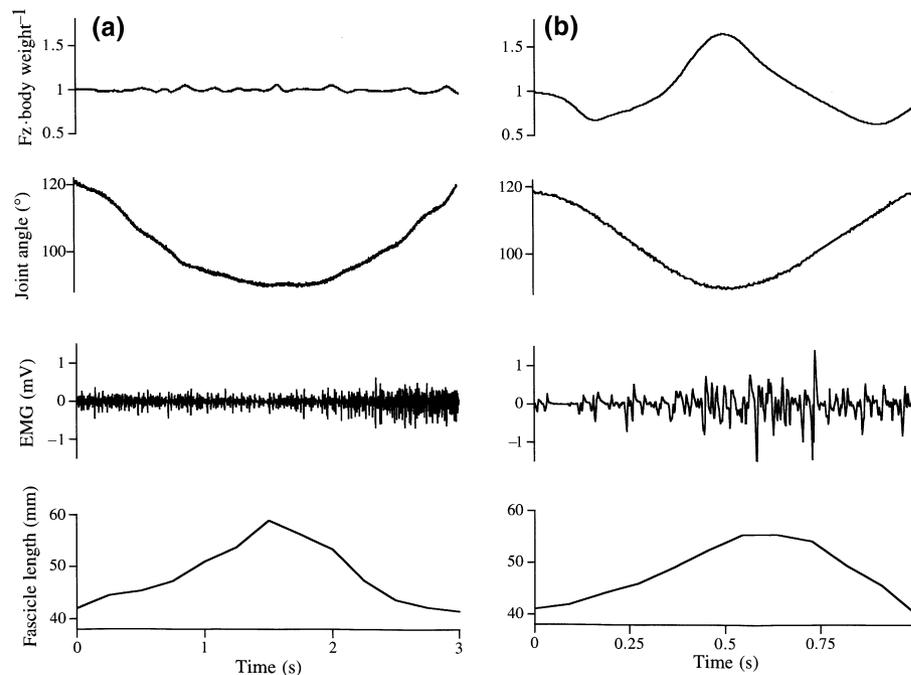
### Statistics

Descriptive data are the mean values  $\pm$  SD. Statistical significance in the differences between two conditions (slow vs. fast), and two phases (dorsi flexion vs. plantar flexion) were analysed using Student's paired *t*-test. A one-way ANOVA with repeated measures was used to detect the significant effects of joint angle on the  $L_{MTC}$ ,  $L_F$  and  $L_T$ . In the event of significant values of *F* in the ANOVA, Tukey's post hoc test of critical difference was used to locate significance between mean values. The level of significance was set at  $P < 0.05$ .

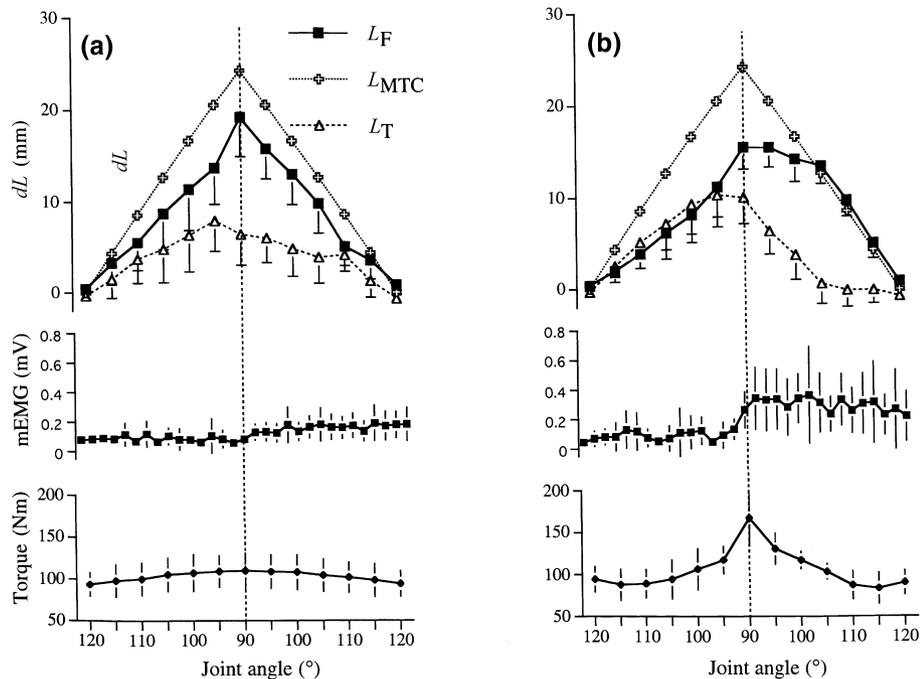
### RESULTS

Figure 3 shows a typical example of the changes in the  $F_z$ ,  $A_j$ , EMG and  $L_F$  during the slow and fast exercises. In the slow exercise, the  $F_z$  and EMG remained almost constant regardless of the changes in the joint angles. On the other hand, the fast exercise produced the peak  $F_z$  as 1.5 times of body weight, and a sudden increase in the EMG activities at the changing phase from dorsi to plantar flexion. There was no time lag between the changes of  $A_j$  and  $L_F$  at the transiting point from dorsi to plantar flexion phase in the two exercises.

The relation between the  $A_j$  and each of TQ, mEMG and dL is shown in Fig. 4. The slow exercise produced few changes in TQ at every joint angle. However, the fast exercise induced a sudden increase at the changing phase from dorsi to plantar flexion. The



**Figure 3** Typical examples of changes in the  $F_z$ ,  $A_j$ , EMG and  $L_F$  during slow (a) and fast (b) exercises. In both exercises, the phase lag of changes in  $A_j$  and  $L_F$  at the changing phase from dorsi to plantar flexion phase were not observed.

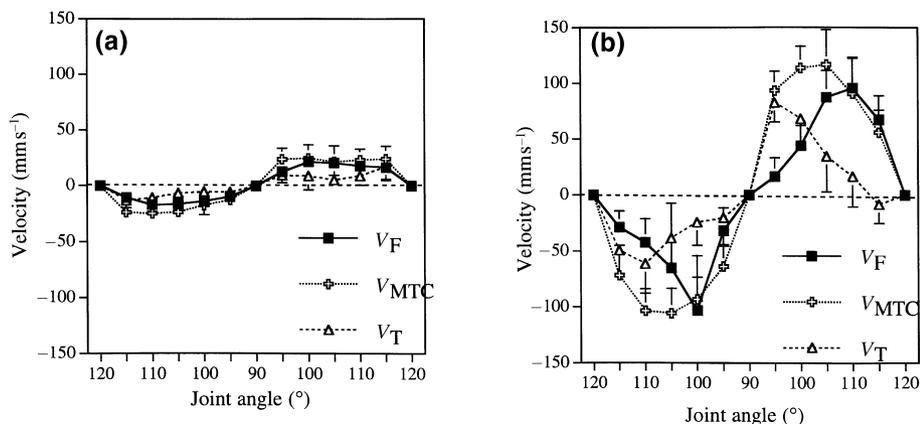


**Figure 4** The changes in the  $L_F$ ,  $L_{MTC}$ ,  $L_T$ , mEMG and TQ during slow (a) and fast (b) exercises. The changing amplitude in  $L_F$  ( $dL_F$ ) was significantly shorter in fast ( $15.4 \pm 2.4$  mm) than in slow ( $19.1 \pm 4.2$  mm). While the  $L_F$  at the same joint angle both during dorsi- and plantar flexion were the same for slow, the  $L_F$  in plantar flexion phase was longer than that in dorsi flexion phase for fast.

peak value in TQ was significantly higher in the fast exercise ( $167 \pm 36$  Nm) than in the slow one ( $109 \pm 20$  Nm). In the two exercises, the  $L_{MTC}$ ,  $L_F$  and  $L_T$  were lengthened during dorsi flexion and shortened during plantar flexion. The changing patterns of  $L_{MTC}$ ,  $L_F$  and  $L_T$  in the slow exercises were similar to each other, being accompanied by almost constant values of mEMG over the entire range of joint angles. On the other hand, the fast exercise produced no significant changes in  $L_F$  in the first half of the plantar flexion phase (joint angles of  $90$ – $105^\circ$ ), even when  $L_T$  abruptly short-

ened and mEMG remained at a higher level as compared with that in dorsi flexion. The  $L_F$  at the changing phase from dorsi to plantar flexion was significantly shorter in the fast exercise ( $54.4 \pm 5.5$  mm) than in the slow one ( $58.2 \pm 5.4$  mm). Inversely, the  $L_T$  at that time was significantly longer in the slow exercise ( $6.4 \pm 3.4$  mm) than in the fast one ( $9.9 \pm 2.8$  mm).

The velocities of MTC, fascicle and tendon structures were determined by means of numerical differential calculus of the changes in the  $L_{MTC}$ ,  $L_F$  and  $L_T$  with respect to time (Fig. 5). The fast exercise produced

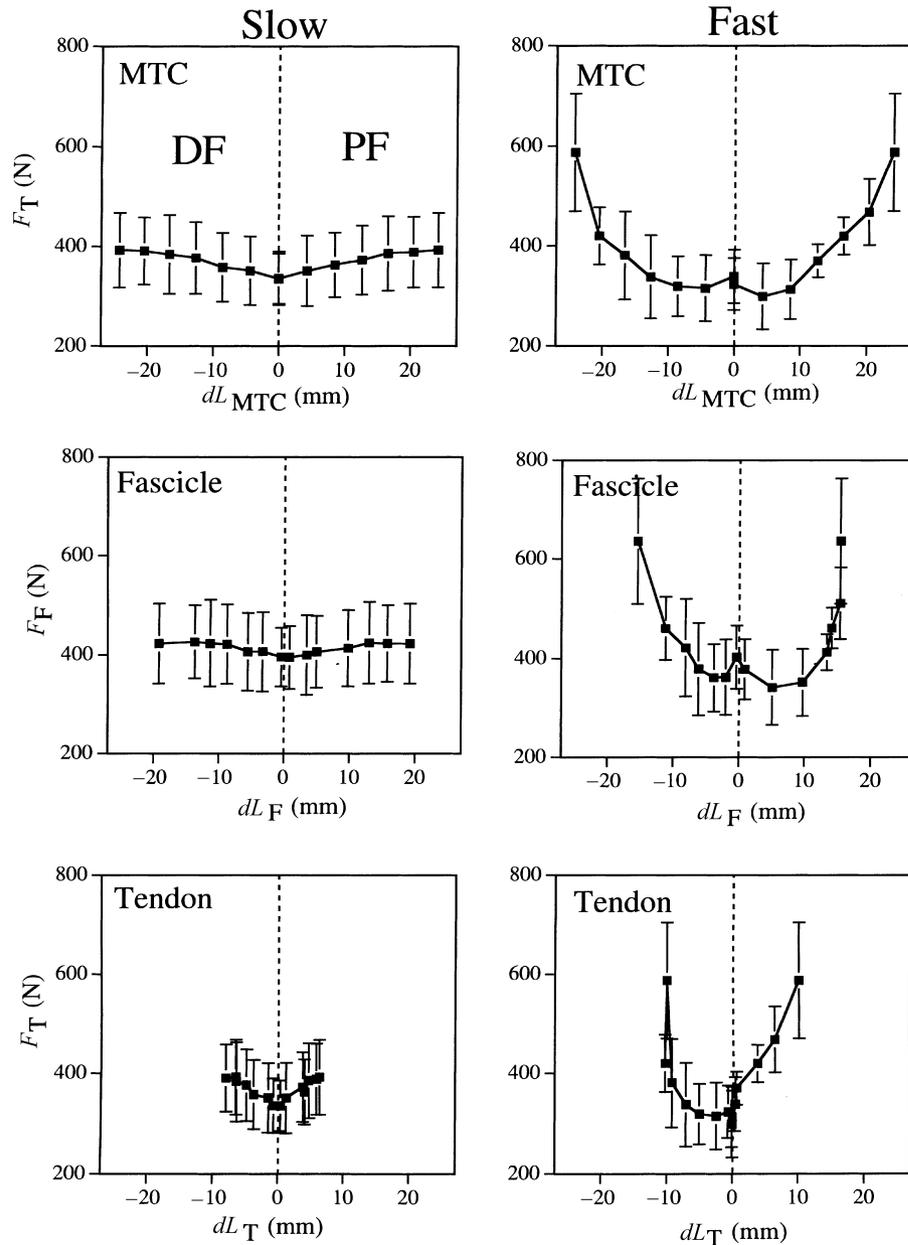


**Figure 5** The changes in velocities of MTC, fascicle and tendon structures ( $V_{MTC}$ ,  $V_F$ ,  $V_T$ ) during slow (a) and fast (b) exercises. In slow exercises, the changing amplitudes in each shortening velocity were considerably smaller. In fast, the rapid shortening of tendon structures control to lower  $V_F$  in the first stage of plantar flexion phase.

a different pattern between fascicle and tendon structures in the change of velocity. Particularly, just after the changing phase from dorsi to plantar flexion, there was a sudden increase in the velocity of tendon structures ( $82.9 \pm 17.3 \text{ mm s}^{-1}$ ) with a relatively low velocity of fascicle ( $16.3 \pm 17.1 \text{ mm s}^{-1}$ ). In the slow exercise compared with the fast one, however, the changes in the velocities of MTC, fascicle and tendon were slight.

The changing patterns during the two exercises in the mechanical work performed by each of MTC,

fascicle and tendon structures are shown in Fig. 6. There was no significant difference in the positive work of MTC between the slow ( $8.4 \pm 1.8 \text{ J}$ ) and fast exercises ( $8.7 \pm 1.6 \text{ J}$ ). The slow exercise produced no significant differences between negative and positive work values in either fascicle ( $7.0 \pm 2.1 \text{ J}$  in negative work vs.  $6.0 \pm 1.5 \text{ J}$  in positive work) or tendon structures ( $1.9 \pm 0.2$  vs.  $2.5 \pm 1.6 \text{ J}$ ). In the fast exercise, however, fascicle performed significantly greater negative work ( $7.1 \pm 2.1 \text{ J}$ ) than positive work ( $5.1 \pm 1.2 \text{ J}$ ), and conversely tendon structure



**Figure 6** The relationship between force and length during slow (left) and fast (right) exercises. Open plots show dorsi flexion, closed plots show plantar flexion. In slow, the curves of  $F_T-dL_{MTC}$ ,  $F_F-dL_F$  and  $F_T-dL_T$  show linear in both dorsi and plantar flexion phases, respectively. In fast, on the other hand, the curves of  $F_T-dL_{MTC}$ ,  $F_F-dL_F$  and  $F_T-dL_T$  show curvilinear, respectively.

performed significantly greater positive work ( $3.7 \pm 1.4$  J) than negative work ( $1.7 \pm 0.9$  J). The tendon structures contributed to 20.2 and 42.5% of the total amount of work executed in slow and fast exercises, respectively.

## DISCUSSION

One of the major findings in this study was that both fascicle and tendon structures were lengthened at the dorsi flexion phase and shortened at the plantar flexion phase, although the pattern of the length changes in the two tissues differed between the slow and fast exercises. In addition, the  $L_F$  at the changing phase from dorsi to plantar flexion was significantly shorter in the fast exercise than in the slow one. This produced a significant difference between the two exercises in  $L_T$  at that time, 6 mm in the slow exercise and 10 mm in the fast one. Using the stiffness of Achilles tendon obtained from cadavers ( $250 \text{ N mm}^{-1}$ ; Benedict *et al.* 1968), however, the calculated elongation length of tendon structures at the changing phase from dorsi to plantar flexion, 3.5 mm in the slow exercise and 5.3 mm in the fast exercise, was shorter than those observed in this study. The tendon structures are separated into the two components of outer tendon and aponeurosis. From the previous findings of tensile testing on isolated animal materials, aponeurosis is more compliant than outer tendon (Ettema & Huijing 1989, Lieber 1991). Recently, Ito *et al.* (1998) showed that one could determine the elasticity of human tendon structures *in vivo* through the ultrasonographical observation of lengthening of the tendon and aponeurosis during muscle contractions. Kubo *et al.* (1999a) reported that the Young's modulus of human tendon structures *in vivo*, which was estimated by ultrasonography with the same procedures used in the present study, was fairly low compared with those observed previously in outer tendons *in vitro*. Applying the stiffness value ( $24 \text{ N mm}^{-1}$ , Kubo *et al.* 1999b) of medial gastrocnemius tendon structures measured *in vivo* to the present data, the calculated elongation length of tendon structures was 7.1 mm in the slow exercise and 10.8 mm in the fast exercise. These values are consistent with the observed  $L_T$  in the present study, suggesting that the observed changes in  $L_F$  and  $L_T$  largely reflected the compliance of aponeurosis. In other words, the present results show that the tendon structures are considerably compliant beyond the level supposed from *in vitro* observations, and that the changes in joint angles during exercise do not necessarily represent those in fascicle (i.e. muscle fibre) length.

The other major finding of this study is that  $L_F$  showed no significant changes in the first half of the plantar flexion phase during the fast exercise. At that

time,  $L_T$  abruptly shortened, and mEMG kept a higher level. These results imply that fascicle acts in nearly 'isometric' conditions just after the end of the transition from dorsi to plantar flexion. Because of the difficulty in examining directly the behaviour of human muscles *in vivo* during contractions, the dynamics of MTC during human exercise have so far been evaluated through modelling and/or simulation approaches (Hof *et al.* 1983, Bobbert *et al.* 1986, Anderson & Pandy 1993, Voigt *et al.* 1995). Bobbert *et al.* (1986) have pointed out that, if tendon structures are not compliant, triceps surae muscles cannot meet with the requirement of combining a high-angular velocity of plantar flexion with a large plantar flexion moment during jumping. Furthermore, previous studies using animals showed that the shortening velocity was lower in muscle fibre than in whole muscle during isokinetic contraction because of more compliant aponeurosis (Lieber 1991, Zuurbier & Huijing 1992). The large extensibility of the aponeurosis has been shown to be used to make muscle contractions more efficient during movements (Roberts *et al.* 1997). In the present study, the fast exercise induced a sudden increase in the shortening velocity of tendon structures just after the ankle joint changed from dorsi to plantar flexion, being accompanied by a relatively low shortening velocity of fascicle. Taking this point into account together with the above quoted findings, the rapid shortening of tendon structures at the first stage of plantar flexion in the fast exercise may be assumed to play a role in lowering the velocity of fascicles to near-isometric conditions. This will enable the working muscles to develop more tension in relation to their force-velocity properties.

It is well documented that, if an activated muscle is stretched prior to shortening, its performance is enhanced during the concentric phase (e.g. Cavagna 1977). The mechanisms underlying such a stretch-induced enhancement of mechanical performance have so far been a matter of controversy. To explain the phenomenon, however, the amount of stored elastic energy has been indirectly evaluated through the measurements of mechanical efficiency (Thys *et al.* 1975, Funato *et al.* 1984) and the kinetics of movement (Komi & Bosco 1978, Bosco *et al.* 1982). Among previous studies on the subject, Funato *et al.* (1984) reported that iEMG of the quadriceps muscles during one cycle of squatting decreased with increasing exercise frequency, which was mainly caused by a decrease in iEMG during the knee-extension phase. They claimed that the decrease in muscle activation was supported by increased elastic energy stored in the muscle. On the other hand, some researchers using simulation approaches have pointed out that the storage and reutilization of elastic energy can be ruled

out as an explanation for the enhancement of performance with prior stretch (Anderson & Pandy 1993, van Ingen Schenau *et al.* 1997). Anderson & Pandy (1993) indicated that the quadriceps femoris and hamstrings developed much larger forces during counter-movement jump than during squat jump, which was accompanied by substantial differences in EMG activities. They concluded that an increase in muscle force in the proximal extensors did not result in a large increase in the amount of elastic energy stored during counter-movement jump, because the more proximal muscles have tendons that are relatively short and stiff. As discussed earlier, however, the present study and recent studies using ultrasonography indicate that human-tendon structures are extensible. Also, we recently observed that the stiffness of tendon structures in vastus lateralis muscle was inversely correlated to the difference in jump height between the vertical jumps performed with and without counter-movements (Kubo *et al.* 1999a). This supports that the elasticity of tendon structures is a factor in the enhanced performances in stretch-shortening cycle exercises.

In addition, the present result on the work performed by fascicle and tendon structures matches the assumption that the elasticity of tendon structures saves the positive work in the stretch-shortening exercises, which fascicle should perform, by functioning to store elastic energy in the negative phase and reuse it in the positive phase. Namely, the slow exercise induced no significant differences between negative and positive work executed by each of the fascicle and tendon structures. In the case of the fast exercise, however, the fascicle performed significantly less positive work than negative work, and conversely tendon structure performed significantly greater positive work than negative work. Furthermore, the tendon structures contributed to 20.2 and 42.5% of the total amount of work executed in the slow and fast exercises, respectively. Bobbert *et al.* (1986) estimated that the muscle fibres, tendon structures and transportation accounted for 30, 45 and 25%, respectively, of the total amount of work completed during one-legged jumping. Similarly, Voigt *et al.* (1995) reported that, using model calculations, the tendons performed 52–60% of the total work during the repetitive jumps. In addition, Belli & Bosco (1992) demonstrated that the percentage of series elastic-component work compared with the external centre of gravity work was 39.8% during vertical jumps. The observed magnitude of the contribution of tendon structures in the present study lies within the range of values reported previously. Thus, we may say that the present approach using ultrasonography can provide direct evidence of the mechanisms which result in a higher mechanical efficiency during stretch-shortening cycle exercises, which have been supposed to be caused

by the storage and reutilization of elastic energy in tendon structures (e.g. Bobbert *et al.* 1986).

In summary, the present results suggest that human tendon structures *in vivo* are compliant beyond the level supposed from *in vitro* observations, and make the dynamics of MTC in stretch-shortening cycle exercises more efficient by changing their lengths. In addition, they show that the use of ultrasonography can clarify the interaction between the fascicle and tendon structures movement in humans.

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