Behaviour of vastus lateralis muscle–tendon during high intensity SSC exercises *in vivo*

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Received 13 November 2002, accepted 27 April 2003
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Abstract

Aims: The interaction between fascicle and tendinous tissue of human vastus lateralis muscle was investigated during varying intensity stretch–shortening cycle (SSC) jumps performed on a sledge apparatus.

Methods: Eight subjects performed single leg squat (SJ) and drop jumps (DJ) from a constant dropping height but to different rebound heights. The fascicle length of the vastus lateralis muscle (VL) was determined from real-time ultrasonography during the movement. Tendon length changes were calculated by subtracting the horizontal part of the fascicle length from the muscle–tendon unit (MTU) length. Simultaneously, kinematic, kinetic and electromyographic data were recorded from leg muscles. In addition, the *in vivo* patella tendon force was measured from one subject during the trials.

Results: In all DJs, where MTU was stretched prior to shortening, the fascicle and tendinous tissue of the VL also underwent a SSC. The fascicle lengths decreased and the recoil of tendinous tissue increased with increased rebound intensities ($P < 0.05$). The force–velocity curves obtained from the MTU showed the expected force–velocity relationship for SSC activities, demonstrating performance enhancement. However, the increased MTU power during the shortening phase of the movement was due primarily to the enhancement of the tendon compartment.

Conclusion: The results of this study show that, at higher rebound intensities, the fascicle is controlled during the braking phase in a distinct manner so that the effective recoil of the tendon is possible during the final push-off phase. In addition, the results suggest that the behaviour of fascicle length change depends on the muscle in question in addition to the movement intensity.

Keywords fascicle, force–velocity, muscle-tendon unit, recoil, stretch–shortening cycle, tendinous tissue, ultrasonography.

In human movement, the stretch–shortening cycle (SSC) is a commonly used muscle action (Norman & Komi 1979, Komi 1990). During the push-off phase (concentric action) of the SSC, power output and efficiency can be greater than in the isolated concentric action. This has been demonstrated in isolated muscle preparations with constant electrical stimulation (Cavagna *et al.* 1965, 1968) and in animal (Gregor *et al.* 1988) and human SSC actions (Komi 1983, Finni *et al.* 2001). Considerable effort has been devoted to explain the mechanisms for this enhancement of force and power during SSC. Cavagna *et al.* (1965) were one of the first to argue that this enhancement could be generated primarily from stored elastic energy. Since that time many additional alternative explanations (Huijing 1992, Komi & Gollhofer 1997, Van Ingen Shenau *et al.* 1997) have been presented.

With respect to the muscle–tendon interaction during the SSC, there are arguments that describe muscle–tendon unit (MTU), fascicle and tendinous tissue (outer tendon and aponeurosis) function in human locomotion. Earlier studies using muscle modelling have shown that muscle length changes differ from those of the MTU. For example, the contractile component has been shown to maintain a constant length (Hof *et al.* 1983), or even shorten (Griffiths 1991), while the MTU is lengthening during the braking phase of an SSC exercise. Fukunaga *et al.* (1997) demonstrated that it is difficult to estimate muscle fibre behaviour solely from observation of joint performance because the fascicle does not behave exactly like the MTU. Therefore, more detailed studies are required to differentiate between muscle fibre and tendon length changes during movement.

Recent developments in ultrasonography (Fukunaga *et al.* 1997) have made it possible to measure *in vivo* fascicle length changes during human movements. Fukunaga *et al.* (2001) examined the behaviour of contractile and elastic components of the medial gastrocnemius muscle (MG) during submaximal activity (human walking). They observed that in these submaximal conditions, the muscle fibres remained isometric after the contact and then the tendinous tissues behaved spring-like for storage and release of elastic energy. In addition, Finni *et al.* (2001) combined *in vivo* patellar tendon force measurements with *in vivo* fascicle length measurements also during submaximal conditions but in different tasks: squat jump (SJ), countermovement jump (CMJ) and drop jump (DJ). The fascicles were shown to be stiffer during the braking phase of DJ compared with that of CMJ. This implies that the fascicle length changes may behave differently depending on the task and exercise intensity and that the results obtained for one specific exercise type could not represent the fascicle behaviour in other conditions. Therefore, the purpose of this study was to examine muscle and tendon behaviour in detail between low- and high-intensity jumping exercises. The jumping height, i.e. the intensity of the push-off phase, was modified to compare the interaction between fascicle and tendinous tissue during SSC with increased rebound intensities.

Methods

Subjects and experimental protocol

Eight male subjects volunteered for this study (age, 25.4 ± 2.0 years; height, 181.1 ± 2.9 cm; body mass, 76.7 ± 4.5 kg). All subjects gave their written consent after being informed of the purpose and risks associated with the study. The study was approved by the Ethics Committee of the University of Jyväskylä.

The subjects were fastened to a sledge apparatus (Kaneko *et al.* 1984, Kyröläinen & Komi 1995) and first tested for unilateral sledge jumps from a squat position (SJ; knee and ankle angle were 105 and 90°, respectively) to find their maximum squat jumping height (SJH). The subjects then performed unilateral DJs from a constant dropping height (80% of SJH) to three different predetermined rebound heights in a random order. The rebound heights were designated as Low (80% of SJH), Mid (90% of SJH), and High (110% of SJH) intensities. The velocity profiles of the sledge displacement in these conditions are shown in Figure 1. In addition, one subject repeated the jumping protocol with an optic fibre force transducer inserted into his patellar tendon in order to measure the *in vivo* force.

Sledge performances

The SJs and DJs were performed on the sledge apparatus with an inclination angle of 20.3° from the horizontal position. During jumping tasks, the subjects were provided with visual feedback in order to maintain the predetermined lowest position of knee angle of 105° (180° is full extension) and the target jumping height

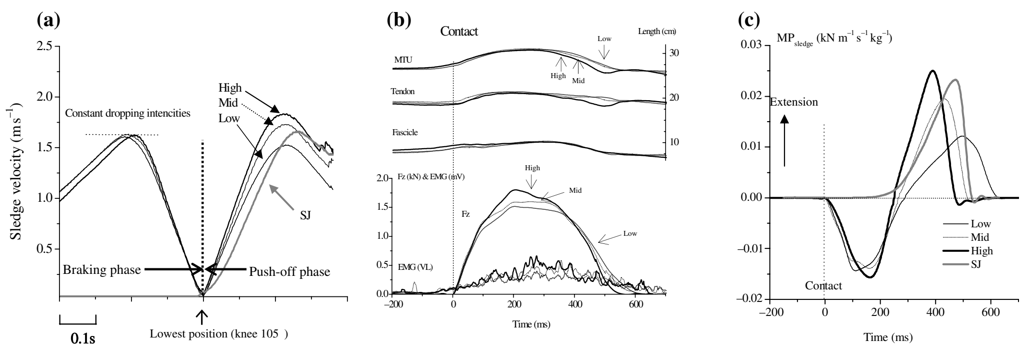

Figure 1 (a) Velocity profiles during maximum squat jump (SJ), and drop jumps (DJs) with different rebound intensities. The peak rebound velocity points show different rebound intensities. (b) Ground reaction force (F_z), VL EMG, and length changes of the muscle–tendon unit (MTU), tendon and fascicle during the different rebound jumps. (c) Mechanical power output (MP_{sledge}) during SJ and DJs (positive values indicate the jumping vector).

(Low, Mid or High). The reaction forces (F_z, perpendicular to the movement plane of the sledge seat), sledge displacement, sledge velocity (V_s), and EMGs from the vastus lateralis (VL) and gastrocnemius medialis (MG) muscles were collected with MOTUS software (Peak Performance Technologies Inc, USA) at a sampling rate of 1 kHz. Bipolar EMG electrodes with an interelectrode distance of 20 mm (Beckmann miniature skin electrodes 650437, USA) were placed on the muscle bellies at locations chosen according to the recommendations of SENIAM (1999). Care was taken that the interelectrode resistance was below 5 kΩ. The EMG was bandpass-filtered (5–500 Hz) and amplified before sampling to a computer. The EMG signals were then full-wave rectified and averaged separately in the pre-activation, braking and push-off phases of the movement. Pre-activation phase was defined as the 100 ms preceding the ground contact (Komi 1987). The braking and push-off phases were determined from the velocity of sledge displacement (Fig. 1a).

The jumping performances were recorded with a videotape at 200 Hz from the right side of the subject. Reflective markers placed the on neck, trochanter major, centre of rotation of knee, lateral malleolus, heel and fifth metatarsal head were digitized using MOTUS software (Peak Performance Inc., USA). The transformed coordinates were filtered digitally with a Butterworth fourth-order zero-lag low-pass filter (cut-off frequency: 8 Hz). An electronic pulse was used to synchronize the analog and kinematic data.

In vivo *fascicle and tendon length measurements with ultrasonography*

With the subjects seated on the sledge apparatus, an ultrasound probe (60 mm, 7.5 MHz, B-mode, Aloka SSD2000 with scanning frequency of 42 Hz) was firmly attached to the mid-thigh immediately above the location of the VL EMG electrode. The real-time images were captured on videotape at 50 Hz and analysed with MOTUS software (Peak Performance Inc, USA). The superior and inferior aponeurosis and a fascicle were identified and digitized from each image (Fig. 2). For each subject, the entire length of the VL fascicle (L_{VL}) was estimated using trigonometry (Finni *et al.* 2001, 2003, Finni & Komi 2002) to make calculation possible. This estimation was necessary because L_{VL} could not be visualized throughout the contact phase of the jumps (Fig. 2). The error for estimating L_{VL} with this method has been reported to be 2–7% (Finni *et al.* 2001, 2003, Finni & Komi 2002). To estimate if the errors in the present experiment are within the range of errors published in these earlier papers, the entire VL muscle images were constructed from recordings of adjacent images collected along the muscle length for three subjects, three trials each. Thus, the real lengths of the fascicle during the contact phase of jumping were compared with those obtained by the linear method in total of nine trials. This comparison revealed that errors of the estimated length and pennation angle were less than 5.9 and 4.5%, respectively. Consequently, it was concluded that the linear extrapolation method could be applied reliably for the contact phase in the present study.

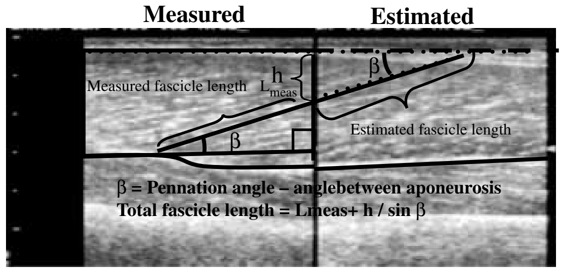

Figure 2 The entire fascicle length (L_{VL}) was estimated using a linear continuation of aponeuroses and fascicles when the fascicle was not fully visible within the imaged area.

The instantaneous lengths of fascicle and tendinous structures were determined on the basis of a geometric MTU model proposed by Allinger & Herzog (1992). The length of tendinous tissues was defined as the sum of the proximal and distal tendinous structures, and aponeuroses (Kurokawa *et al.* 2001, Muraoka *et al.* 2001).

Length changes in the tendinous tissue (tendon and aponeurosis; L_T) were calculated as

$$L_T = L_{MTU} - L_{VL} \cdot \cos \alpha$$

where L_{MTU} is the MTU length and α is the angle between fascicle and deeper aponeurosis (Fukunaga *et al.* 2001, Kurokawa *et al.* 2001). Length changes in L_{MTU} were calculated from knee joint angular data using the model of Hawkins & Hull (1990).

In vivo *force measurements with optic fibre technique*

Direct tendon forces from patellar tendon were measured for one subject with the optic fibre technique. This technique and the analysis procedures have been described in detail elsewhere (Komi *et al.* 1996, Arndt *et al.* 1998, Finni *et al.* 1998, 2001). In these measurements, tendon deformation during locomotion modulates the intensity of the light transmitted through the optic fibre. Changes in light intensity have been shown to have linear relationship with the external force. In the present study, the optic fibre was calibrated with the knee fixed at 120°. Before the sledge jumps, the calibration was performed with 10, 20, 30 and 40% MVC. After the measurements, the calibration was performed with additional levels of effort until the maximum effort was reached. In agreement with earlier studies (Komi *et al.* 1996, Arndt *et al.* 1998; Finni *et al.* 1998, 2001) a good linear fit ($r = 0.97$) was observed between the external force and the fibre output. The vastus lateralis muscle force (F_{VL}) and vastus lateralis fascicle force (F_{Fa}) in the direction of the muscle fibres (fascicles) were then deduced from patellar tendon force (Ichinose *et al.* 2000, Finni *et al.* 2001, 2003):

$$F_{VL} = \mathrm{PTF} \cdot 34\%, \quad \mathrm{PTF} \cdot 34\% (\cos \alpha)^{-1}$$

where α is the angle between the deep aponeurosis and the fascicle, and 34% is considered as a relative physiological cross-sectional area (PSCA) of VL to the total PSCA of quadriceps femoris muscle (Akima *et al.* 1995).

Calculations

The mechanical power (MP_{sledge}) was calculated for the braking and push-off phases by multiplying F_z and V_s (see Fig. 1c). The velocities of the MTU, fascicle and tendinous tissue were calculated by differentiating the corresponding length change value with time; the shortening of the MTU, fascicle and tendinous tissue was defined as positive. To calculate the positive mechanical power produced by the MTU and tendinous tissue, F_{VL} was multiplied by the velocities of the MTU and tendinous tissue, respectively. Similarly, F_{Fa} was multiplied by the fascicle velocity to calculate the positive mechanical power of the fascicle. Positive mechanical work done by MTU, fascicle and tendinous tissue was calculated by the numerical integration of the corresponding mechanical power values (Kurokawa *et al.* 2001).

Treatment of data

Mean, standard deviation (SD), and Pearson's two-tailed correlations were calculated. One-way ANOVA with Tukey's *post hoc* test was used, when appropriate, to reveal significant differences between pre-activation, braking and push-off phases or between variables at the different rebound conditions. The level of significance was set at $P < 0.05$.

Results

Changes in mechanical parameters

Typical examples of the mechanical parameters during the SJ and different DJs are shown in Figure 1. In these DJ performances, the dropping height was kept constant, but the target rebound intensity (height) was varied. Consequently, the reaction force patterns were similar but the peak forces were significantly ($P < 0.05$) greater in the High rebound intensities compared with the Low rebound intensities (Fig. 3). The peak MP_{sledge} was also greater in the High than in the Low condition (negative phase $P < 0.05$, positive phase $P < 0.01$). The increased rebound intensity had significant effects on the push-off velocity and contact time (Fig. 3). The contact times of the push-off phase of every DJ were shorter than that of SJ ($P < 0.01$). Measured parameters in SJ were similar to Low DJ but differed significantly from High DJ (Fig. 3). For example, the peak push-off velocity of High, the peak F_z of Mid and High and the positive peak MP_{sledge} of High were significantly higher than those of SJ (Fig. 3).

Fascicle length and tendon length changes

During the braking-phase of DJ, the MTU, fascicle and tendinous tissue lengthened for every DJ condition (MTU: 3.8 ± 1.1, 3.6 ± 1.0, 3.2 ± 0.8 cm; fascicle: 1.9 ± 1.5, 1.8 ± 1.5, 1.4 ± 1.0 cm; tendinous tissue:

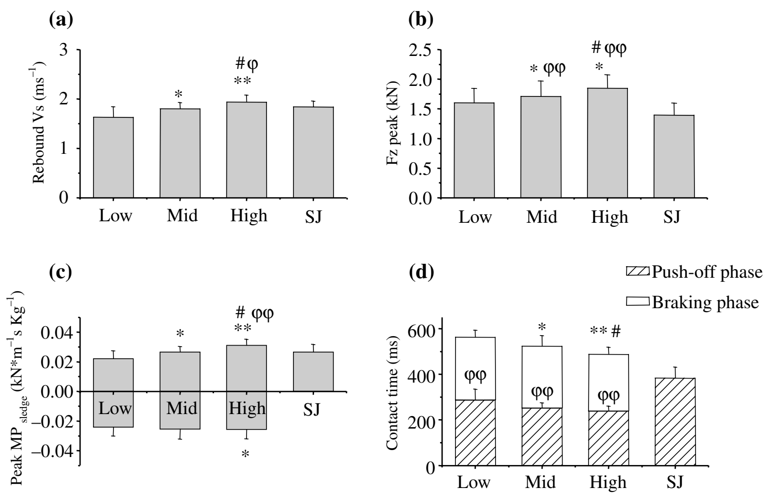

Figure 3 Changes in the sledge mechanical parameters during squat jump (SJ) and drop jumps (DJs) for all subjects ($n = 8$). (a) Rebound sledge velocity; (b) peak ground reaction force; (c) peak mechanical power (peak MP_{sledge}); (d) contact time (range of slash line is contact time in the push-off phase). *, ** Significantly different from Low at $P < 0.05$ and $P < 0.01$, respectively. # Significantly different from Mid at $P < 0.05$. φ,$\varphi\varphi$ Significantly different from SJ at $P < 0.05$ and $P < 0.01$, respectively.

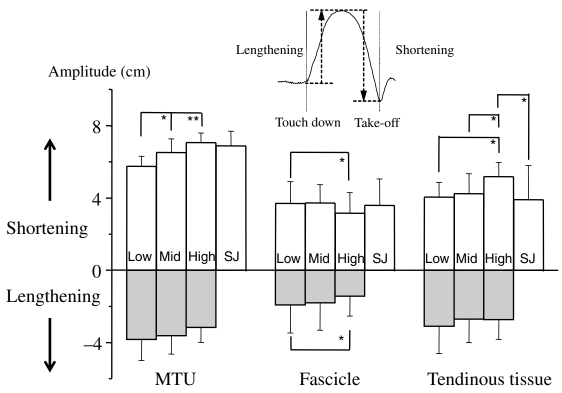

Figure 4 Length change amplitudes of MTU, fascicle and tendon (tendinous tissue) in the braking and push-off phase during squat jump (SJ) and drop jumps (DJs). We defined the lengthening and shortening as the length change amplitudes from the length at the touch down moment to the peak length and from the peak length to the length at the take off moment. *,** Significantly different at $P < 0.05$ and $P < 0.01$, respectively.

3.1 ± 1.5, 2.7 ± 1.3, 2.7 ± 1.1 cm in Low, Mid and High, respectively). In the push-off phase, MTU, fascicle and tendinous tissues shortened for each condition (MTU: 5.7 ± 0.5, 6.5 ± 0.7, 7.0 ± 0.5 cm; fascicle: 3.6 ± 1.2, 3.7 ± 1.0, 3.1 ± 1.1 cm; tendinous tissue: 4.0 ± 0.8, 4.2 ± 1.1, 5.1 ± 0.7 cm, in Low, Mid and High, respectively) (Fig. 4). The changes in fascicle length induced by increasing the rebound intensity differed from those in MTU and tendinous tissue (Fig. 4). In the push-off phase, the amount of fascicle shortening decreased significantly ($P < 0.05$) when the rebound intensity was increased. However, the MTU and tendinous tissue lengthened to a greater extent for the High condition compared with the Low and/or Mid conditions. Similarly to the mechanical parameters, significant differences in the magnitude of fascicle and tendinous tissue length changes were observed in both the push-off and braking phases, where the amount of fascicle lengthening decreased ($P < 0.05$) with increased rebound intensities. The MTU and tendinous tissue length changes did not differ significantly between conditions during the braking phase (Fig. 4). The peak lengthening and shortening velocities in the MTU, fascicle, and tendinous tissue are shown in Table 1. The peak lengthening velocities of the MTU and tendinous tissue did not change significantly with the increased rebound intensity, however, the fascicle velocities decreased. The peak shortening velocities of the MTU, fascicle, and tendinous tissue were not different between the various DJ conditions. In addition, as shown in Figure 4, the shortening amplitude of tendinous tissue at High was greater than that of SJ ($P < 0.05$). The peak shortening velocity of the MTU and tendinous tissue in the Low and Mid conditions were lower than in SJ. However, the shortening amplitude and peak shortening velocity of fascicle length were not significantly different as compared with SJ.

EMG activity

The average EMG for the VL was the same across conditions during the pre-activation phase, but increased in the braking phase at High ($P < 0.05$) and in the push-off phase at Mid ($P < 0.05$) and High ($P < 0.01$) compared with Low (Table 2). The average EMG for the VL in the push-off phase of High was higher ($P < 0.05$) than that of SJ and that of Low was lower than that of the SJ ($P < 0.05$). Similarly, an EMG of MG muscles tended to increase during the braking and push-off phases with increasing rebound intensity (Table 2).

Table 1 Measured velocities of the length change in MTU, fascicle and tendinous tissue ($n = 8$)

	Low	Mid	High	SJ
Peak lengthening velocity (cm s^{-1})				
MTU	27.3 ± 3.5	25.6 ± 4.9	25.4 ± 6.2	
Fascicle	25.2 ± 8.9	22.2 ± 8.8	17.9 ± 8.1*	
Tendon	29.9 ± 12.4	24.9 ± 4.9	24.1 ± 8.2	
Peak shortening velocity (cm s^{-1})				
MTU	46.8 ± 10.0#	60.0 ± 8.7*,##	76.4 ± 7.8**,††	70.9 ± 18.4
Fascicle	29.7 ± 15.1	33.4 ± 12.1	33.3 ± 11.3	30.1 ± 14.6
Tendon	31.7 ± 9.7#	33.4 ± 13.6#	52.4 ± 10.5**,††	51.4 ± 19.9

Values are expressed as means ± S.D.
*,**Significantly different from Low at $P < 0.05$ and $P < 0.01$ respectively.
†,††Significantly different from Mid at $P < 0.05$ and $P < 0.01$ respectively.
#, ##Significantly different from SJ at $P < 0.05$ and $P < 0.01$ respectively.

Table 2 Average aEMG values (mV) of each phase during DJ and SJ ($n = 8$)

Phase	Low	Mid	High	SJ
Vastus Latelaris (VL)				
Pre-activation	0.04 ± 0.04	0.06 ± 0.06	0.05 ± 0.06	
Braking	0.27 ± 0.07	0.29 ± 0.06	0.33 ± 0.09*	
Push-off	0.34 ± 0.09#	0.43 ± 0.08*	0.51 ± 0.09**,#	0.42 ± 0.13
Medial Gastrocnemius (MG)				
Pre-activation	0.14 ± 0.08	0.13 ± 0.08	0.15 ± 0.08	
Braking	0.12 ± 0.06	0.12 ± 0.06	0.15 ± 0.08	
Push-off	0.17 ± 0.08#	0.22 ± 0.10	0.23 ± 0.11*	0.24 ± 0.05

Values are expressed as means ± S.D.
*,**Significantly different from Low at $P < 0.05$ and $P < 0.01$ respectively.
#, ##Significantly different from SJ at $P < 0.05$ and $P < 0.01$ respectively.

In vivo *muscle-tendon behaviour*

Figures 5 and 6 show the force–velocity and force–length relationships for the MTU, fascicle, and tendinous tissue during the contact phase of the DJ and the push-off phase of the SJ ($n = 1$). The force–velocity relationship for the MTU showed the typical curve observed during SSC exercises (Gregor *et al.* 1988, Komi *et al.* 1992, Komi 2000, Finni *et al.* 2001). In the MTU level, force and velocity increased during the shortening phase with the increased rebound intensities and the force at the beginning of the push-off phase was higher for the DJ compared with the SJ (Fig. 5a). Also, for the fascicle and tendinous tissue levels, the force at the beginning of the push-off phase was greater for the DJ than the SJ (Fig. 5b and c). There were no clear differences in the fascicle force–velocity relationships between the DJs. In the MTU, however, the force enhancement could be seen at higher shortening speeds. With the increased rebound intensities, the instantane-

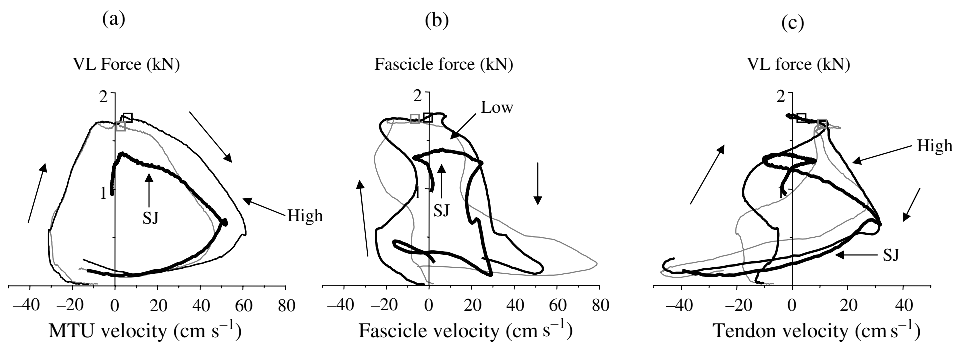

Figure 5 MTU (a), fascicle (b) and tendon (c) force–velocity relationships during squat jump and drop jumps (SJ, Low and High). The squares indicate the transition from the braking phase to the push-off phase.

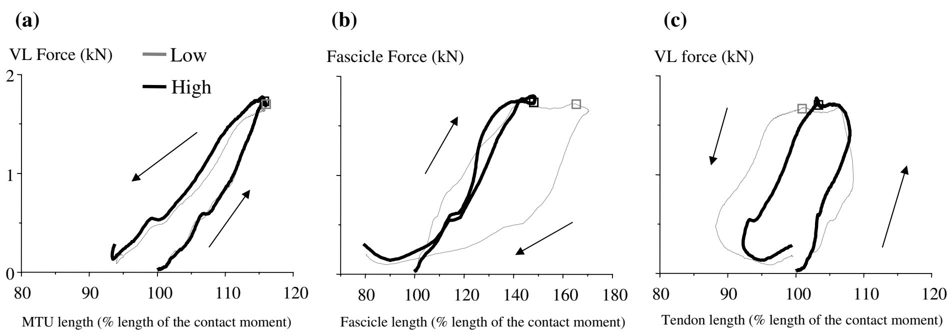

Figure 6 MTU (a), fascicle (b) and tendon (c) force–length relationships during different rebound jumps.

ous fascicle force–length curve became steeper (Fig. 6b), but the peak F_{VL} and F_{Fa} did not clearly show difference. The amount of positive mechanical work done by the MTU increased with higher rebound intensities but that of the fascicle decreased and that of the tendinous tissue increased (MTU: 46.8, 47.6, 48.8 J; fascicle: 43.4, 43.4, 17.3 J; tendinous tissue: 3.8, 4.7, 31.8 J in Low, Mid and High, respectively, $n = 1$).

Discussion

In the present DJ performances, the rebound jumping heights were varied with the constant dropping height. We compared the interaction between fascicle and tendinous tissue during SSC with increased rebound intensities. One important finding was that the fascicle and tendinous tissues of VL underwent SSC action in all DJs, where MTU was stretched prior to shortening (Fig. 1). This finding is consistent with results from low-intensity SSC exercises (Finni *et al.* 2001). Another important finding was that the fascicle length decreased and the amount of tendinous tissue shortening increased with higher rebound intensities (Fig. 4). Thus, the recoil of tendinous tissue was clearly shown at the end of the push-off phase, especially for the conditions with higher rebound intensity. Finni *et al.* (2001) reported that the fascicles were stiffer for the DJ condition than either the countermovement jump or squat jump. Other researchers have also shown that the fascicle length behaved differently depending on the task (Kawakami *et al.* 2002). Together, these findings suggest that the fascicle length can be regulated during ground contact to enhance tendinous tissue recoil. It should be emphasized, however, that the fascicle length regulation might depend on intensity as well as the task.

In the present study, we also measured the *in vivo* patella tendon force from one subject. The force–velocity curves obtained from the MTU had the expected relationship for SSC activities (Komi 1990, Finni *et al.* 2001). Force and velocity of the MTU level increased in the shortening phase with the increased rebound intensities (Fig. 5a). A more detailed examination of the fascicle and tendinous tissue length changes revealed that their behaviours were different when the rebound intensity was varied. The power enhancement of the MTU during the shortening phase with higher rebound intensities was too great to be the result of fascicle power output alone. Therefore, the power production of the tendinous tissue must play an important role through elastic recoil. The changes of interaction between the fascicle and tendinous tissue with higher rebound intensities were probably caused by the regulation of the fascicle length, whose force–length curves were steeper with higher rebound intensities (Fig. 6b). This steeper slope means higher stiffness in the stretching phase. Thus, although the dropping height was constant in all trials, the fascicle became stiffer in the braking phase with increased EMG activities during the knee flexed. Therefore, the fascicle was stretched less even though the push-off intensity was increased.

Another important point is that the fascicle was lengthened further without additional force development after rising to the peak force level in the Low rebound condition (Fig. 6b). This additional lengthening could result in less elastic energy recovered by the passive recoil of tendinous tissue at the beginning of the push-off phase. Consequently, this fascicle yielding could reduce the contribution of elastic energy to control the rebound intensity. This result clearly supports the idea that the elastic recoil of the mechanical energy in the SSC is decreased if the coupling time is long (Cavagna *et al.* 1965, 1994, Bosco *et al.* 1981).

It must be emphasized that the observed results apply only to the VL muscle and to the SSC exercises used in this study. Within this limitation, the present results confirm the hypothesis that in SSC the performance enhancement results from the fascicle length operating effectively to make the tendon recoil possible in the push-off phase.

Compared with the present results, previous studies have reported only a small length increase, or even shortening of MG muscle fibre, during the braking phase in animal movements (Griffiths 1991, Roberts *et al.* 1997). During human walking, the MG fascicles have been found to contract nearly isometrically during the braking phase (Fukunaga *et al.* 2001, Kawakami *et al.* 2002). The majority of the previous studies have examined only one muscle. However, the mechanical behaviour of muscle and tendon may be specific to a given MTU. If this is the case, it would be difficult to generalize the fascicle behaviour from the results of one muscle only. Therefore, we compared the behaviour of MG (MTU, fascicle and tendinous tissue) with that of VL from one subject who performed the identical jumping protocol with the ultrasound probe also on his gastrocnemius medialis muscle. Figure 7 shows the data of this comparison. It was observed that the tendinous tissues of both muscles showed rapid shortening (recoil) in the end of the push-off phase at higher rebound intensity. In the fascicle level, the VL fascicle behaved similarly as shown in Figure 1, but in agreement with Fukunaga *et al.* (2001), the MG fascicle behaved isometrically throughout the contact phase at lower rebound intensity. Although the average VL and MG EMGs were similar in every phase (Table 2), the fascicle length changes showed different patterns between these two muscles. Thus, the mechanical behaviour of the different compartments may not depend only on the task and intensity,

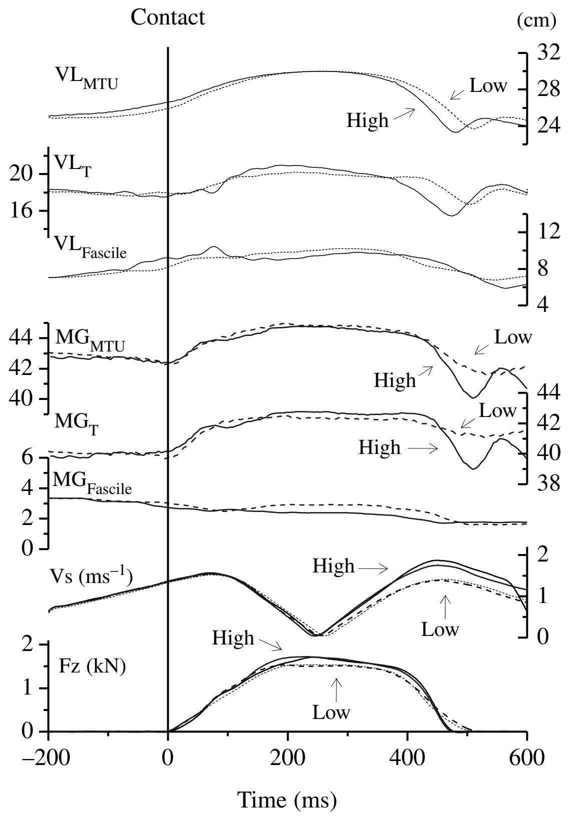

Figure 7 Example of MTU, fascicle tendon length changes in vastus lateralis and gastrocnemius muscles with reaction forces (F_z), sledge velocities (V_s) during the drop jumps of Low (dashed line) and High (solid line).

but perhaps on the muscle in question as well. As the MG is a two-joint muscle, it is possible that the monoarticular muscle (soleus) affecting the same ankle joint could behave differently from its synergistic MG.

The recoil of elastic energy during walking has been suggested to be meaningful (Gregor *et al.* 1988, Fukashiro *et al.* 1995, Roberts *et al.* 1997). The capacity for elastic energy storage in muscle is limited but the tendinous structures can store and recoil appreciable amount of elastic energy (Alexander & Bennet-Clark 1977, Morgan *et al.* 1978). In the present study, the force development of tendinous tissue continued during the shortening phase in DJ but not in SJ (Fig. 5c). The force levels of the MTU, fascicle and tendinous tissue at the beginning of the push-off phase were greater for all of the DJs compared with the SJ (Fig. 5). Bobbert *et al.* (1996) have shown in simulation studies that the greater jumping height in CMJ than in SJ could result from a greater force level reached prior to the concentric phase. Similarly, Finni *et al.* (2000, Fig. 10) reported a positive relationship between tendon force in the end of the eccentric phase and the concentric peak power. However, in their study the force development of the patella tendon continued during the push-off phase in CMJ. Consequently, they suggested that greater force at the end of the braking phase may not be the only reason for greater SSC jumping performance as compared to SJ. In fact, the present results also showed that the jumping height in SJ was greater than in Low, but the force level of MTU is higher in Low than in SJ at the beginning of the push-off phase. Consequently, the SSC performance could not result only from the given MTU and fascicle force levels at the beginning of the push-off phase, but it may also be affected by the continued increase of tendinous force during the shortening phase.

Conclusions

When the SSC performance was enhanced with increased rebound intensities, the VL fascicle and tendinous tissue behaved similarly to the MTU; i.e. they were stretched prior to shortening. However, with increased rebound intensities, the length change amplitude of fascicle decreased and the tendinous tissue recoil was clearly seen at the end of the push-off phase. The present results confirm the hypothesis that in the SSC the performance enhancement results from the fascicle length operating effectively to make the tendon recoil possible in the push-off phase. In addition, it should be taken into consideration that fascicle length changes could depend not only on intensity and task but also on the muscle in question.

The study was supported by a grant # 192/722/2001 (Komi) from the Ministry of Education, Finland. The authors would like to acknowledge the assistance of Dr Vesa Lepola, Mr Sami Kuitunen, Ms Pirkko Puttonen, Ms Marja-Liisa Romppanen, Ms Sirpa Roivas and Mr Markku Ruuskanen. Dr Michael Grey is thanked for his comments in the final phases of the manuscript preparation.

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