Interaction between fascicle and tendinous tissues in short-contact stretch-shortening cycle exercise with varying eccentric intensities

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Ishikawa, M., E. Niemelä, and P. V. Komi. Interaction between fascicle and tendinous tissues in short-contact stretch-shortening cycle exercise with varying eccentric intensities. J Appl Physiol 99: 217–223, 2005. First published February 10, 2005; doi:10.1152/japplphysiol.01352.2004.—The interaction between fascicle and tendinous tissues (TT) in short-contact drop jumps (DJ) with three different drop heights [low (Low), optimal (OP), and high (High)] was examined with 11 subjects. The ground reaction force (F<sub>r</sub>) and ankle and knee joint angles were measured together with real-time ultrasonography (fascicle length) and electromyographic activities of the medial gastrocnemius (MG) and vastus lateralis (VL) muscles during the movement. With increasing drop height, the braking force and flight time increased from Low to OP (P < 0.05). In High, the braking force increased but the flight time decreased compared with OP (P < 0.05). During contact of Low and OP conditions, the length of muscle-tendon unit and TT underwent lengthening before shortening in both MG and VL muscles. However, the two muscles differed in the fascicle behaviors. The MG fascicles behaved isometrically or shortened, and the VL fascicles underwent lengthening before shortening during contact. In High, the TT lengthening in both muscles decreased compared with OP (P < 0.05). The rapid stretch occurred in the MG fascicles but not in VL fascicles during the braking phase. The elastic recoil ratio decreased in both muscles with increasing the intensity during DJ. These findings demonstrated that TT underwent lengthening before shortening during DJ. However, the efficacy of elastic recoil decreased with increasing the drop intensity. The effective catapult action in TT can be limited by the drop intensity. In addition, the measured muscles behaved differently during DJ, providing evidence that each muscle may have a specific means of fascicle-TT interaction.

METHODS

Subjects and experimental protocol. Eleven physically active men and women [age 23.8 yr (SD 1.5), height 169 cm (SD 7.4), body mass 64.3 kg (SD 8.0)] participated in this study. They all had previous experience with the execution of drop jumps. All of them were fully informed of the procedures and risks associated with the study. The study was approved by the Ethics Committee of the University of the Jyväskylä.

Techniques similar to previous studies (1, 25, 30) were used in various jump performances. Our subjects were instructed to put their very best effort in all jump conditions. The subjects dropped themselves directly on the force platform from erect standing on different elevations and subsequently rebounded upward (Fig. 1). The subjects were dropped from different heights to identify the best individual height of rise of the center of mass, which was then used as the optimal drop height. Thereafter, they more readily, because the current ultrasound methods can be applied to measure directly length changes of the fascicle-tendinous tissues (TT; outer tendon and aponeuroses) during in vivo human movements (12, 20, 21, 23, 28).

Recent studies have reported that the recoil of TT is clearly increasing with increasing the drop intensity during DJs on the sledge apparatus (20) or in countermovement jumps (23, 28, 41). However, these DJ exercises have a relatively longer contact time (>400 ms) than, e.g., in running and hopping. Primarily because of the resonant frequency of elastic component in the ankle extensors in humans (3.33 ± 0.15 Hz) (2), the question arises whether the elastic recoil is performed at all in the short-contact DJ exercises. Generally, viscoelastic material is stronger and stiffer at increasing strain rates. For the same maximal force level, this means that less storage of elastic energy may occur at higher strain rates.

Ishikawa et al. (20) added additional arguments to the problem of the fascicle behavior during DJs. They reported that the fascicles of the medial gastrocnemius (MG) and vastus lateralis (VL) muscles behave differentially during DJs.

The present study was designed to examine the behavior of fascicle-tendinous tissue interaction during the extreme high drop intensity load DJ exercises and to clarify the relative contribution of elastic recoil in tendon during the short-contact time DJ exercises. We hypothesized that, in contrast to the longer contact time jumps, as described above, the short-contact stretch-shortening cycle (SSC) exercises cannot utilize the elastic energy effectively. Instead it will rely more on the stretch load intensity, but only up to a certain critical point, beyond which the efficacy of the elastic recoil decreases. Additionally, it is believed that the fascicle-TT interaction in DJ may be muscle specific.
performed drop jumps from three individually predetermined dropping heights randomly: optimal drop height (OP), optimum plus 10 cm (High), and optimum minus 10 cm (Low).

**Measured parameters.** In the drop jumps, the subjects were video recorded with a high-speed video camera (200 frames/s) for the right side perpendicular to the line motion. Video records were used to calculate the joint angles of the lower limb (hip, knee, and ankle). Reflective markers were placed on the right side of subject (Fig. 1) and digitized with Motus software (Peak Performance Technologies). Ground reaction forces and center of pressure under the foot were recorded by means of a force plate (Kistler, model 9281B). Simultaneously, electromyographic (EMG) signals were recorded from the midbellies of the MG, tibialis anterior (TA), and VL muscles in the right leg by using miniature surface bipolar electrodes (Ag/AgCl; the interelectrode resistance was below 5 kΩ) and sent telemetrically to the recording computer (12-bit analog-to-digital converter) with a sampling frequency of 1 kHz. Care was taken that the interelectrode resistance was below 5 kΩ.

Longitudinal sectional images of the MG and VL muscles were obtained by using a real-time ultrasound apparatus (SSD-2000, SSD-5500, Aloka, Japan). One linear array probe (scanning frequency of 7.5 MHz) was fixed firmly at a proximal part of the lower right leg (~30% of the distance from the popliteal crease to the center of external malleolus), and another probe (scanning frequency of 7.5 MHz) was fixed at the midthigh after the visibility of the echoes from fascicle interspaces in MG and VL during movement were secured because of the differences in the two ultrasound instruments. The images during the exercises were obtained at the rates of 50 and 96 images/s in the MG and VL muscles, respectively (Fig. 1B). These images were further analyzed with Motus software (Peak Performance Technologies). The MG and VL fascicles identified along their length (L_{fa, MG} and L_{fa, VL}, respectively) from the superficial and deep aponeurosis were tracked continuously frame by frame. Assuming a linear continuation, we calculated the total L_{fa, VL} by estimating the part of the fascicle that was not visible (8, 20, 21). The fascicle angles in MG and VL muscles were determined as the angle between the deep aponeurosis and the line drawn tangentially to the fascicle. The error for estimating the entire length of fascicle was ~0–6% as measured from images of the whole VL muscle. The reliability and reproducibility of the fascicle length measurement with the ultrasound method have been confirmed elsewhere (7, 8, 11, 12, 15, 20–23, 28).

**Analisys.** Instantaneous net joint moments around ankle and knee joints were calculated through inverse dynamics (44). Net joint moments in the direction of plantar flexion and in the direction of knee extension were defined as positive and were referred to as “plantar flexion moment” and “knee extension moment,” respectively.

The model of Hawkins and Hull (14) was used to estimate the lengths of the MTU of MG (L_{MTU,MG}) and VL (L_{MTU,VL}) by applying the individual segment lengths in the calculations using the ankle and knee joint angles. The instantaneous lengths of TT (outer tendon and aponeuroses) in MG (L_{TT,MG}) and VL (L_{TT,VL}) were calculated with the following equations (12, 20, 21, 27, 28):

$$L_{TT} = L_{MTU} - L_a \times \cos \alpha$$

where L_{TT}, L_{MTU}, and L_a are TT, MTU, and fascicle length, respectively, and α is angle between the fascicle and the deep aponeurosis.

The instantaneous moment arms for the Achilles tendon and the quadriceps tendon were estimated by the similar calculation (36, 38). The Achilles tendon force (ATF) and quadriceps tendon force (QTF) were calculated as the net joint moments divided by the instantaneous tendon moment arm. It was assumed that ATF was further reduced to the relative physiological cross-sectional area (PCSA) of the MG in the Achilles tendon as follows (27, 28):

$$ATF_{MG} = 0.154 \cdot \left(M_{ankle} \cdot d_A^{-1}\right)$$

$$F_{fascicle,MG} = ATF_{MG} \cdot \cos \alpha_{MG}^{-1}$$

where ATF_{MG} is tendon force in MG and F_{fascicle,MG} is tensional forces of MG, M_{ankle} indicates the ankle moment, d_A is moment arm of MG, \(\alpha_{MG}\) is fascicle angle of MG, and 0.154 is PCSA of MG (15.4%) relative to the total PCSA of the total plantar flexors (10).

The shortening direction of the MTU, fascicle, and TT was defined as positive. The mechanical power was calculated by velocities of the length changes (MTU, fascicle, and TT) and tendon and fascicle forces in MG and VL, respectively. The mechanical works done by MTU, fascicle, and TT were calculated by the numerical integration of the corresponding mechanical power values (20, 28).

The EMG signals were full-wave rectified and filtered (fourth-order Butterworth low-pass filter at 50 Hz). The averaged EMGs (aEMG) were calculated in the following three phases: preactivation, braking, and push-off phases. The preactivation phase was defined as 100 ms preceding ground contact (26). The braking and push-off phases were separated from the horizontal ground force data. The averaged EMG for the short-latency stretch reflex (SLR) component of MG and VL.
muscles were identified by the duration from 30- to 60-ms latency after ground contact (6, 18).

The specially constructed electronic pulse was used to synchronize ultrasound images and data of kinematics and kinetics. All the data (after EMG signals were rectified and filtered) from three trials in each condition were averaged. Coefficients of variation of three trials were in the ranges of 0–2% in the ankle and knee joint angle data, and 0–2% in the $L_{fa,MG}$ and 0–5.3% in the $L_{fa,VL}$, respectively, on the three trials.

Treatment of data. Means and standard deviation values were calculated for the various parameters. After synchronization of the curves of three trials in each condition of each subject on the instant of contact, representative curves of values in each condition of each subject were averaged. The ANOVA for repeated measurements on one factor and post hoc least significant difference multiple comparisons were used to reveal significant difference between the different drop intensity conditions. If the normality test was failed, one-way repeated ANOVA on ranks was used. The Spearman’s rank correlation coefficient for polynomial regression analysis of variables was used. The probability level for statistical analysis was set at $P < 0.05$.

RESULTS

Changes in the mechanical parameters. Figure 2 presents typical curves of mechanical parameters during the contact of three different intensity DJs. With increasing drop intensity, the peak of the vertical ground reaction force ($F_z$) the slope of $F_z$, the estimated $ATF_{MG}$, and QTF of the FL (until OP) increased ($P < 0.05$, Table 1). The contact time increased in High compared with Low and OP ($P < 0.05$). The flight time increased from Low to OP ($P < 0.05$) and then decreased from OP to High ($P < 0.05$).

Changes in EMG activities. Typical time courses of EMG activities are shown in Fig. 2A in different conditions. The aEMGs of MG in preactivation increased in OP than in Low and did not show significant difference between OP and High (Table 2). However, the EMG activities in MG decreased around the contact moment in all subjects (Fig. 2A). The preactivation aEMG in VL increased slightly in High as the drop intensity increased ($P < 0.05$). In the braking phase, aEMG in MG, VL, and TA decreased from Low to High. In the push-off phase, the aEMG in MG decreased from Low to OP and increased from OP to High. VL and TA did not show any significant difference during the three conditions. The SLR amplitude in MG decreased in High, but that in VL increased in High (Table 2).

Length changes in MTU, fascicle, and TT of MG and VL. Figure 2, B and C, shows typical time courses of the length data in MTU, fascicle, and TT in VL and MG during three different conditions. The fascicles in MG in VL followed the different length change patterns throughout contact. Before the contact,
the MG fascicle shortened, but not the VL fascicles. During contact, MG fascicles continued to shorten or remained at the same length but the VL fascicles underwent lengthening before shortening to follow the concept of SSC (24). The exception for this behavior was the MG fascicle in the High condition. The MG fascicle in High was suddenly stretched at 30–50 ms after the ground contact. In the subsequent push-off phase, the MG fascicle shortened again compared with OP. On the TT level, both muscles underwent lengthening before shortening during contact.

Figure 3 shows the amplitudes of lengthening and shortening in MTU, fascicle, and TT during the different DJ conditions. Compared with Low, MG fascicles shortened less in OP during the braking and push-off phases ($P < 0.05$). The VL lengthening and shortening amplitudes were smaller in OP than in Low ($P < 0.05$). In TT, the lengthening amplitudes of both muscles were higher in OP than Low. This TT shortening to follow the concept of SSC (24). The exception for this behavior was the MG fascicle in the High condition. The MG fascicle in High was suddenly stretched at 30–50 ms after the ground contact. In the subsequent push-off phase, the MG fascicle shortened again compared with OP. On the TT level, both muscles underwent lengthening before shortening during contact.

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Figure 4 shows changes in the lengthening and shortening velocities during contact of the tendinous tissues in MG and VL muscles at the three drop jump conditions. The mean TT shortening velocities in VL are higher than the lengthening of that (P < 0.05) during all three conditions. In MG, the mean TT shortening velocity is higher than the lengthening one in Low (P < 0.05). In High, however, the TT behavior of MG shows the opposite result.

### Table 1. Measured and estimated mechanical parameters

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>OP</th>
<th>High</th>
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</thead>
<tbody>
<tr>
<td>Contact time, ms</td>
<td>221 (SD 22)</td>
<td>224 (SD 33)</td>
<td>233 (SD 32)*</td>
</tr>
<tr>
<td>Braking phase, ms</td>
<td>95 (SD 12)</td>
<td>92 (SD 21)</td>
<td>99 (SD 17)*</td>
</tr>
<tr>
<td>Push-off phase, ms</td>
<td>126 (SD 18)</td>
<td>132 (SD 23)</td>
<td>133 (SD 20)</td>
</tr>
<tr>
<td>Flight time, ms</td>
<td>467 (SD 48)</td>
<td>481 (SD 47)*</td>
<td>451 (SD 54)*</td>
</tr>
<tr>
<td>Peak Fz, N</td>
<td>3,428 (SD 606)</td>
<td>3,891 (SD 874)*</td>
<td>5,316 (SD 1,775)**</td>
</tr>
<tr>
<td>The slope of Fz, °</td>
<td>72.2 (SD 46.8)</td>
<td>90.4 (SD 43.8)*</td>
<td>124.9 (SD 64.0)*†</td>
</tr>
<tr>
<td>Peak ATFMG, N</td>
<td>569 (SD 263)</td>
<td>609 (SD 316)*</td>
<td>920 (SD 573)*†</td>
</tr>
<tr>
<td>Peak QTF, N</td>
<td>5,089 (SD 1,970)</td>
<td>5,878 (SD 2,622)*</td>
<td>5,510 (SD 3,010)</td>
</tr>
</tbody>
</table>

Values are as means (SD); n = 11 subjects. Low, OP, and High, low, optimal, and high drop heights, respectively; Fz, vertical ground reaction force; ATFMG, Achilles tendon force in the medial gastrocnemius (MG); QTF, quadriceps tendon force; TT, tendinous tissue; VL, vastus lateralis. *Significantly different from Low; †significantly different from OP.

### Table 2. aEMG in preactivation, braking, and push-off phases and the average amplitudes of SLR area

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>OP</th>
<th>High</th>
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</thead>
<tbody>
<tr>
<td>aEMG in MG, mV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>0.20 (SD 0.11)</td>
<td>0.28 (SD 0.12)*</td>
<td>0.28 (SD 0.14)</td>
</tr>
<tr>
<td>Brake</td>
<td>0.27 (SD 0.13)</td>
<td>0.26 (SD 0.13)</td>
<td>0.24 (SD 0.14)*</td>
</tr>
<tr>
<td>Push-off</td>
<td>0.27 (SD 0.12)</td>
<td>0.24 (SD 0.10)*</td>
<td>0.28 (SD 0.14)*†</td>
</tr>
<tr>
<td>aEMG in VL, mV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>0.08 (SD 0.04)</td>
<td>0.09 (SD 0.05)</td>
<td>0.11 (SD 0.05)*</td>
</tr>
<tr>
<td>Brake</td>
<td>0.51 (SD 0.27)</td>
<td>0.52 (SD 0.28)</td>
<td>0.47 (SD 0.21)*†</td>
</tr>
<tr>
<td>Push-off</td>
<td>0.44 (SD 0.27)</td>
<td>0.42 (SD 0.25)</td>
<td>0.42 (SD 0.24)</td>
</tr>
<tr>
<td>aEMG in TA, mV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>0.14 (SD 0.09)</td>
<td>0.14 (SD 0.09)</td>
<td>0.15 (SD 0.09)</td>
</tr>
<tr>
<td>Brake</td>
<td>0.10 (SD 0.08)</td>
<td>0.09 (SD 0.06)</td>
<td>0.08 (SD 0.05)*</td>
</tr>
<tr>
<td>Push-off</td>
<td>0.08 (SD 0.05)</td>
<td>0.09 (SD 0.05)</td>
<td>0.08 (SD 0.06)</td>
</tr>
<tr>
<td>SLR amplitude, mV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MG</td>
<td>0.28 (SD 0.15)</td>
<td>0.25 (SD 0.12)</td>
<td>0.22 (SD 0.10)*†</td>
</tr>
<tr>
<td>VL</td>
<td>0.46 (SD 0.24)</td>
<td>0.53 (SD 0.26)</td>
<td>0.58 (SD 0.28)*</td>
</tr>
</tbody>
</table>

Values are means (SD); n = 11 subjects. aEMG, averaged EMG; SLR, short-latency stretch reflex; TA, tibialis anterior. *Significantly different from Low at $P < 0.05$; †significantly different from OP at $P < 0.05$.
stretching work in TT) in MG decreased with increasing intensity during the short-contact DJs (Table 1). The ratio in VL (<2.5) in the present short-contact DJ is smaller than the value (>3.0) reported for this muscle in long-contact SSC exercises [the work in TT of VL was calculated in the same way as Ishikawa et al. (20)]. This may suggest that the efficacy of elastic recoil in TT can decrease with increasing stretch loads in the short-contact SSC exercises. Consequently, the effective catapult action in TT of the short-contact SSC can be limited by the drop intensity.

Muscle-specific regulation of the fascicle length. The observed different patterns of the fascicle length changes between MG and VL muscles can be considered as another new finding in the present study. The VL muscle especially followed the “normal” SSC action during ground contact. It was stretched in all conditions (Low, OP, and High) first and then shortened in the push-off phase. The MG muscle, however, followed a different pattern in this regard. In general, its fascicles continued shortening or remained at constant length during the entire contact phase. The exception for this behavior was the High condition, which is to be discussed later. There are arguments in the literature suggesting that the fascicles can maintain a constant length (3, 16, 12, 23, 35), shorten (13, 17, 28), or even lengthen (7, 20, 21) during the early phase of the ground contact of SSC exercises. The present study was designed to measure the two muscles simultaneously by using two different ultrasound probes. Thus it can be concluded that generalization of fascicle behavior during human locomotion cannot be made from one specific muscle only. The question arises whether this different behavior may reflect the possible difference between mono- and biarticular muscles. Interestingly, our recent unpublished material shows that when the ultrasound measurements were performed simultaneously for the MG and soleus muscles, the soleus fascicles behaved in the same manner as the VL muscle in the present study (Sousa F, Ishikawa M, and Komi PV, unpublished observations). How these possible functional differences in the two types of musculature may be related to observed differences in the fascicle level behavior needs to be explored more thoroughly. This is especially important given that the biarticular muscle (MG) offsets the lengthening and shortening effects during the braking phase of the present SSC movements. The MTU stretching in MG was relatively smaller

![Fig. 3. Length changes of MTU, fascicle, and TT in MG and VL from contact moment to peak length (gray bar; lengthening) and from peak length to takeoff moment (white bar; shortening). MG fascicle lengthening was defined as the length changes from contact to the end of braking phase, and shortening was defined as the length changes from the end of braking phase to the takeoff. Significant differences, P < 0.05, from Low (*) and from OP (#) (n = 11).](image-url)
The fascicle shortening work may be enhanced by reattachment much more rapidly during the push-off phase (9, 32, 42). The fascicle shortening in MG started at 30–50 ms after contact. In the Sub. B, the MG fascicle started to lengthen after the peak MG fascicle force (F\text{fascicle,MG}). In the Sub. F, the MG fascicle started to lengthen after the reduction of the F\text{fascicle,MG}.

It is naturally puzzling what causes this sudden MG fascicle lengthening. We have observed in a pilot experiment sudden lengthening of the MG fascicle during the end of the braking phase of a DJ performed from 80-cm height (Koivunen J and Komi PV, unpublished observation). As discussed earlier, the MG muscle in the present study responded to the High condition differently compared with two other drop levels (Low and OP). When the drop height exceeded the optimal stretch load condition, the MG fascicles were suddenly stretched. Our estimated ATF values of 10–12 times body weight in High are considerably higher than those of eccentric contractions (34, 35). The effective catapult action in TT before being suddenly overstretched. On the other hand, in VL muscle, the rapid increase of the VL fascicle was not observed because the impact peak QTF did not increase in High (Fig. 2).

In conclusion, during the short-contact DJs, TT underwent lengthening before shortening during contact. However, the efficiency of elastic recoil decreased with increasing the drop intensity. The effective catapult action in TT of the short-contact SSC can be limited by the drop intensity. In addition, the measured fascicles in two muscles showed the different

As noted above, the possible interference from the GTO during extreme impact cannot be excluded. Unfortunately, the EMG records and their analysis could not conclusively show that the reduction in the SLR amplitude was related to the reduction in mechanical behavior of the MG muscle in this High impact load. Many studies have, however, suggested that reduction of performance in the extreme load drop jump condition may be due to the group Ib afferent inhibition from GTO (33, 43). In the present study, two subjects showed that the rapid fascicle lengthening in MG occurred before reaching the peak ATF\text{MG}. In all other subjects, this lengthening started after the peak ATF\text{MG} reduction (Fig. 5). In the latter case, the fascicle stretch occurs after the possible Ib inhibition from GTO. In the former case, the reported mechanism could be related to the situation in which the detachment or slipping of cross bridges may have reached a critical limit of force before Ib discharges from GTO. Admittedly, this is all speculation at the present stage of these studies in progress. However, one may conclude that two mechanisms, Ib inhibition and cross-bridge detachment (slipping), may be operative either together or independently during the sudden fascicle stretch of MG in High.

It appears that the fascicle behavior in the MG muscle is as an overall concept dependent on the stretch load intensity. If we draw the length changes of the MG fascicle against the ATF slope measured for the same time period as the sudden stretch occurred in High, we obtain the relationship shown in Fig. 6. This quadratic relationship may be indicative of the critical stretch load for MG (y-axis = 0, Fig. 6) to maintain the concerted action with TT before being suddenly overstretched. On the other hand, in VL muscle, the rapid increase of the VL fascicle was not observed because the impact peak QTF did not increase in High (Fig. 2).

In conclusion, during the short-contact DJs, TT underwent lengthening before shortening during contact. However, the efficiency of elastic recoil decreased with increasing the drop intensity. The effective catapult action in TT of the short-contact SSC can be limited by the drop intensity. In addition, the measured fascicles in two muscles showed the different
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