Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise

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Ishikawa, Masaki, and Paavo V. Komi. Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. J Appl Physiol 96: 848–852, 2004. First published October 31, 2003; 10.1152/japplphysiol.00948.2003.—This study examined whether the elasticity of the tendinous tissues plays an important role in human locomotion by improving the power output and efficiency of skeletal muscle. Ten subjects performed one-leg drop jumps (DJ) from different dropping heights with a constant rebound height. The fascicle length of the vastus lateralis muscle was measured by using real-time ultrasonography during DJ. In the braking phase of the DJ, fascicle lengthening decreased and the tendinous tissue lengthening increased with increased dropping intensity. In the subsequent push-off phase, the shortening of tendinous tissues increased with higher dropping intensity. The averaged electromyographic activities of the preactivation and braking phases increased and those of the push-off phase decreased as the drop height was increased. With higher dropping height but constant submaximal rebound jump, the stretched tendinous tissue length increased with less stretched fascicle during the braking phase. In the subsequent push-off phase, the recoil of tendinous tissues became greater. These results suggest that the increased prestretch intensity has considerable influence on the process of storage and subsequent recoil of the elastic energy during the stretch-shortening cycle action.

METHODS

IN HUMAN MOVEMENT, muscles usually undergo lengthening before shortening. This combination of lengthening and shortening actions is called stretch-shortening cycle (SSC) action (31). It has been stressed that elastic energy stored in muscle-tendon unit complexes (MTU) during the braking phase of an SSC enhances mechanical efficiency and power output during the push-off phase (3, 9, 25, 30). It has been shown that the force is potentiated in SSC in human knee extension muscles when the coupling time between the stretch and shortening became smaller (28). Mechanical efficiency of SSC exercises has also been reported to be higher than that of pure concentric exercises (10, 11). Efficiency of the positive work reportedly ranges from 40 to 80% for running and other SSC exercises (11, 22, 33, 34, 36). The difference of these efficiency values could be affected by the prestretch intensity and the intensity of subsequence concentric phase (12).

In human movements, mechanical and metabolic effects have been examined under varying intensity SSC exercises, and the results showed that the elastic energy can be utilized and metabolic demands reduced when the prestretch intensity is increased (4, 5, 10). These results, however, have referred to the whole leg extension movement or to the MTU. Studies that examined these phenomena on muscle fiber and tendon levels had utilized indirect estimation (7, 40).

On the basis of isolated muscle experiments, it is clear that muscle efficiency varies with the nature of contractile conditions (6). It is of interest to examine how the separate compartments (contractile and elastic components) change in length during SSC. This is because the length change in MTU does not necessarily coincide with the length changes experienced by muscle fascicle and tendinous tissues during SSC (15, 17, 21). It is important to examine the interaction between muscle and tendinous tissues and its effects on the process of storage and subsequent recoil of elastic energy during SSC.

In the present study, we examined further the effects of the fascicle and tendinous tissue length changes of the vastus lateralis muscle (VL) by varying the prestretch intensity but keeping the following concentric work constant during SSC exercises.

METHODS

Subjects. Ten healthy male volunteers, who were very well trained on sledge jumps, participated in this study (age 26.4 ± 2.4, height 178.1 ± 2.7 cm, body mass 73.2 ± 4.0 kg). They were informed of all the risks associated with this study, which was approved by the Ethics Committee of the University of Jyväskylä, and they also gave their written consent to participate.

Experimental protocol and parameters measured. In the sledge apparatus (23), the subjects performed unilateral drop jumps (DJ). The inclination of the sledge was 20.3° from the horizontal position. The subjects were first tested for unilateral sledge jumps from a squat position (SJ; knee and ankle angle were 105 and 90°, respectively; 180° is full extension) to find their maximum squat jumping height (SIH) for determination of the target rebound jumping height (80% of SJH). Four different dropping heights were then designated as Low (80% of SJH), Mid (90% of SJH), High (110% of SJH), and Max (130% of SJH) intensities. The subjects performed these unilateral DJS from the predetermined different dropping intensity (Low, Mid, High, and Max) to a constant rebound height (80% of SJH) in a random order. During jumping tasks, the subjects were provided with visual feedback from the television monitor for the purpose of controlling the predetermined lowest position of the knee angle of 105° and the target jumping height. The velocity profiles of the sledge displacement in these conditions are shown in Fig. 1.

Reaction forces (perpendicular to the movement plane of the sledge seat), sledge displacement, velocity of sledge displacement, and electromyographic (EMG) activity from the VL, rectus femoris, gastrocnemius medialis, and soleus muscles were collected with Motus software (Peak Performance Technologies) at a sampling rate of 1 kHz. EMG activity was recorded from the midbellies of the above

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muscles (surface electrodes with a diameter of 5 mm and interelectrode distance of 20 mm). Care was taken that the interelectrode resistance was below 5 kΩ. The EMG signals were full-wave rectified and then low-pass filtered at 75 Hz (Butterworth type fourth-order low-pass digital filter). The trials were recorded onto a videotape at a frequency of 200 Hz from the right side of subject. Reflective markers were placed on neck, trochanter major, center of rotation of the knee, lateral malleolus, heel, and fifth metatarsal head. These reflective markers were automatically digitized by using Motus software (Peak Performance), which then gave values for the joint angles (hip, knee, and ankle). The transformed coordinates were filtered digitally with a Butterworth type fourth-order low-pass filter (cutoff frequency: 8 Hz).

With the subject seated in 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 midthigh immediately above the location of the VL EMG electrode. The real-time images were collected to a videotape at 50 Hz to be analyzed with Motus software (Peak Performance). The superior and inferior aponeurosis and a fascicle were identified and digitized from each image (14, 21). The reliability of the ultrasound method of the fascicle length has been established elsewhere (21, 25, 32).

Data collection and processing. The EMG signals were averaged (aEMG) separately in the preactivation, braking, and push-off phases of the movement. The preactivation phase was defined as the 100-ms period preceding the ground contact (29). Braking and push-off phases were determined from the velocity of sledge displacement (Fig. 1).

For every subject, the entire length of the VL fascicle ($L_{fa}$) was estimated by trigonometry (14, 21) because $L_{fa}$ could not be visualized throughout the contact phase of the jumps. Usually only one fascicle has been analyzed from the ultrasound images (14, 15). In the present study, however, the fascicle length measurements were taken for three different fascicles, and the values were then averaged. The reliability of the present fascicle length technique has been represented earlier to

![Fig. 1. Changes of the mechanical parameters (A–D) between different drop height conditions. Low, Mid, High, and Max: 80, 90, 110, and 130%, respectively, of maximal squat jumping height. **Significantly different at $P < 0.01$.](http://jap.physiology.org/)

![Fig. 2. Averaged EMG activities of the preactivation (Pre), braking, and push-off phases of 4 different drop conditions. VL, vastus lateralis (A); MG, medial gastrocnemius (B); SOL, soleus (C); RF, rectus femoris (D). * and **Significantly different from Low at $P < 0.05$ and $P < 0.01$, respectively.](http://jap.physiology.org/)
be of the order of 0–7% for estimating the entire length of fascicle (14, 21). Length changes in the tendinous tissue (tendon and aponeurosis; $L_T$) were calculated as $L_T = L_{MTU} - L_{fa}\cos\alpha$ ($L_{MTU}$ is the muscle-tendon unit length, and $\alpha$ is the angle between fascicle and deeper aponeurosis) (15, 32). The model of Hawkins and Hull (18) was used to determine the length changes in $L_{MTU}$ from the knee joint angular data.

Treatment of data. Means ± SD were calculated. ANOVA for repeated measurements on one factor and then post hoc least significant difference multiple comparison were used, when appropriate, to reveal significant differences between variables at the different dropping conditions. We considered $P < 0.05$ statistically significant.

RESULTS

The protocol was planned so that the dropping height was varied, but the target rebound height was kept constant for all of the four DJ performance conditions. The results showed that this condition was met as shown in Fig. 1. There were no significant differences between different conditions in the knee joint angles at the contact moment and the lowest position. The net impulse during the push-off phase remained unchanged. However, the dropping velocity of sledge displacement and net impulse during the braking phase increased with increasing drop height. The aEMGs of all examined muscles in the preactivation, braking, and push-off phases changed markedly at higher drop height conditions. Figure 2 shows that aEMGs of the preactivation and braking phases usually increased and those of the push-off phase decreased as the drop height was increased.

In all the measured DJs, fascicle and tendinous tissue length changes followed the MTU length changes. All these compartments underwent stretching before shortening to follow the concept of SSC (31). Although the lengthening and shortening amplitudes of MTU did not show any differences in the measured conditions, those of the fascicle and tendinous tissues clearly changed with the increased dropping intensity (Fig. 3). During the braking phase, the changes of fascicle lengthening were smaller and those of tendinous tissues greater with increased dropping intensity. In contrast, the shortening $L_{fa}$ from the peak $L_{fa}$ was greater in Low than in other conditions. The shortening changes of $L_T$ from the peak $L_T$ increased with increased dropping intensity.

DISCUSSION

The efficiency of the positive work during SSC movement can be increased with higher prestretch intensity (4). The present study was aimed at looking at the “efficiency” from the interaction between fascicle and tendinous tissues during DJ under various dropping intensity conditions.

In the testing protocol, the range of the MTU length changes remained unchanged under the different dropping-height conditions. However, the extent of stretching and shortening in fascicle and tendinous tissues was different depending on the dropping intensity. As the dropping height increased, the stretching of the fascicle during the braking phase decreased with increased EMG in the preactivation and braking phases. These results are in agreement with previous reports that the increased EMG activities during prestretch enhance muscle stiffness (16, 35, 39). As the dropping intensity increased, the stretching of the tendinous tissues during the braking phase increased while the fascicles became stiffer. In the subsequent push-off phase, which always resulted in the same push-off height, the shortening of the tendinous tissues increased with increased dropping intensity. The stiffer fascicle contraction (short change in length) with the effective stretching of tendinous tissues during SSC is known as “concerted contraction” (19, 25). Additionally, the peak fascicle length appeared during the push-off phase in Low, Mid, and High conditions. These changes followed the MTU length changes. All these compartments underwent stretching before shortening to follow the concept of SSC (31). Although the lengthening and shortening amplitudes of MTU did not show any differences in the measured conditions, those of the fascicle and tendinous tissues clearly changed with the increased dropping intensity (Fig. 3). During the braking phase, the changes of fascicle lengthening were smaller and those of tendinous tissues greater with increased dropping intensity. In contrast, the shortening $L_{fa}$ from the peak $L_{fa}$ was greater in Low than in other conditions. The shortening changes of $L_T$ from the peak $L_T$ increased with increased dropping intensity.
results could indicate that the partial potential energy from increased dropping height is utilized effectively by the elastic stretching in regulating the fascicle stiffness and the recoil of tendinous tissues.

In the present study, the rebound intensity was constant and submaximal (80% SH) in all the trials. In the high dropping condition, fascicles lengthened during the middle of the push-off phase. Also, EMG activities during the push-off phase were smaller with higher dropping intensity in a manner previously reported (4). It must be noted that VL EMG activity was clearly much reduced at the middle of the push-off phase (Fig. 4). These results can only be valid to support the concept of higher efficiency if the timing of the muscle relaxation is optimal for the effective release of elastic energy during SSC (13). In the low dropping condition, however, effective storage of energy and its release from the tendinous tissues could not be operative because the EMG activity remained higher and its duration longer in the push-off phase. This could imply that the stored elastic energy was smaller in the low drop-height condition than in the other conditions because of the low level of inertia, gravity, or any other external forces. It must be noted, however, that an optimal drop height may be reached differently among subjects, because in the maximal drop height condition some subjects could not increase the lengthening and subsequent shortening of the tendinous tissues during the contact phase. Their fascicles were stretched more in Max than in High during the braking phase, and their fascicle shortening was greater in Max than in High during the push-off phase (Fig. 4). These observations may suggest inhibition for the protective function from the increased stretch load because the maximal drop condition is too high for them (38, 41). Another possibility for these observations could be related to the contractile properties of muscle. The actin-myosin interaction in cross bridges could be detached when the force exceeds a certain level (20). This may also explain why there is an individual optimum for the jumping performance to be increased when the drop height is increased (27).

The slope of the relation between EMG activity and force is less in skeletal muscle undergoing stretching (eccentric) action compared with shortening (concentric) action (8, 26). Alexander (1) calculated the metabolic rate per unit force against muscle contraction and showed that with higher muscle shortening speed the metabolic rate dramatically increases but is affected only slightly by increasing lengthening speed. In the present results, the fascicle lengthening and shortening were smaller with increased dropping intensity. The observation that a stiffer fascicle may help reuse of elastic recoil for the tendinous tissues in higher prestretch condition can support the concept of the improved efficiency of positive work during SSC (4). In maximal drop height condition, however, fascicle shortening increased in some subjects. In fact, we have preliminary data to show sudden dramatic stretching of the fascicle in extremely high DJ conditions (Koivunen J and Komi PV, unpublished observations). This would suggest braking of the cross bridges under these extreme stretch load conditions. Consequently, mechanical output from the tendinous tissues during the push-off phase could decrease in the supramaximal DJS. These observations may explain the discrepancies that the efficiency of positive work improves (11), remains constant (22), or even decreases (24) with higher prestretch intensity.

One must be aware of the possibility that these results could not be generalized for all skeletal muscles. It has been reported earlier (21) that VL and gastrocnemius muscles may not necessarily demonstrate similar patterns in fascicle length changes in DJ situations. Although in the present study the EMG patterns of all the examined muscles (VL, rectus femoris, gastrocnemius medialis, and soleus) were very much similar in terms of their changes between different jump conditions, they cannot be used to describe fascicle behavior.

In summary, when the dropping height increased with the constant submaximal rebound jump, the stretched tendinous tissue length increased with less stretched fascicle during the braking phase. In the subsequent push-off phase, the recoil of tendinous tissues increased. These results confirm that the partial potential energy from increased dropping height is utilized effectively by the elastic stretching in regulating the fascicle length and the recoil of tendinous tissues.

The present results suggest that the increased prestretch intensity has considerable influence on the process of storage and subsequent recoil of the elastic energy during the SSC.

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