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Contribution of the tendinous tissue to force enhancement during stretch–shortening cycle exercise depends on the prestretch and concentric phase intensities

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Abstract

When the prestretch intensity and concentric work are increased in stretch–shortening cycle (SSC) exercises, the utilization of the elastic energy can increase during the concentric phase. In order to further understand this process during SSC exercises, the interaction between fascicle–tendinous tissues (TT) of the vastus lateralis (VL) muscle was examined under different prestretch and rebound intensity drop jumps. Ten male subjects participated in the study. Direct VL fascicle lengths ($N = 10$) and in vivo patellar tendon force ($N = 1$) were measured together with the electromyographic (EMG) activity of VL during the trials. With increasing drop height but the same rebound height condition, the TT stretch increased during the early braking phase with a subsequent increase in its recoil during the early push-off phase. This occurred concomitantly with decreased fascicle shortening and EMG activation. However, with the increased rebound height but the same drop height condition, the fascicles were stretched less during the late braking phase with higher EMG activation. In this situation, TT could be stretched more by the tension provided by fascicles. Consequently, the TT recoil increased during the late push-off phase. These observations confirm that there can be an intensity specific fascicle–TT interaction during SSC exercises.

Keywords: Muscle fiber; Ultrasonography; Drop jump; Elastic energy; Optic fiber

1. Introduction

A ‘‘natural’’ type of muscle function where the muscle undergoes active stretching prior to shortening during human movements is called a stretch–shortening cycle (SSC) [37]. Studies in both isolated muscle [10,11,13] and in vivo human experiments [5,10,29] have shown that due to the active stretch (eccentric action) the performance in SSC is enhanced over that of pure isometric or shortening (concentric) muscle actions. Elastic potentiation has often been suggested as a reason for the performance potentiation of the SSC. Consequently, the SSC action can improve the power output and efficiency of locomotion [5,8,10,12,20,32]. As the efficiency of SSC is dependent on the prestretch and concentric phase intensities [9], it is of interest to know how the lengths of separate compartments in a muscle (contractile and elastic components) interact during SSC. This information would be valuable in evaluating the contribution of tendinous tissue (TT; outer tendon and aponeuroses) in performance potentiation during the SSC exercises. Clarification may be provided by examining mechanics of the interaction between contractile and elastic components during SSC exercises with different intensities. This can be done when vertical jumps, for example, are performed with different prestretch and subsequent concentric phase intensities. Our previous studies [25,26] suggested that there can indeed be an intensity specific interaction between fascicle and TT during the SSC exercises. To clarify the intensity specific interaction during SSC exercises, the present study was designed to test the hypothesis that the interaction between fascicle and TT

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depends on the prestretch and concentric phase intensities in the SSC exercises in the same subject group. Especially important is to test how the behavior of TT responses to changing prestretch and concentric phase intensities.

2. Methods

2.1. Subjects and the experimental protocol

Ten physically active males volunteered for this study: age 26 ± 3 yr, height 1.80 ± 0.05 m, and body mass 76.1 ± 4.1 kg (mean ± SD). 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.

A special "sledge apparatus" was employed so that the prestretch and concentric work intensities of the one-leg jumps could be well controlled. The jumps were always performed unilaterally both during the SSC exercise and in testing. To get more insight into the tendon loading during these exercises, one of the subjects repeated the jumps with an in vivo force transducer in the patella tendon.

The subjects first performed unilateral sledge jump from squat position (SJ; knee and ankle angles were 105° and 90°, respectively) with maximal effort [18,20]. The reference drop and rebound heights were predetermined as 80% of the maximum jumping height of the SJ. Two kinds of drop and rebound heights were then determined in order to examine how the fascicle–TT interaction is regulated in two different conditions: (1) when the concentric work is increased but the preceding prestretch work is maintained constant and (2) when prestretch work is increased but the subsequent concentric work is kept constant (Fig. 1). The determined jumping heights were as follows:

(1) the reference drop (80% of the jumping height of the maximal SJ) and higher rebound (110% of the jumping height of the maximal SJ) height condition (R_{High});
(2) the higher drop (110% of the jumping height of the maximal SJ) and reference rebound height (80% of the jumping height of the maximal SJ) condition (D_{High});
(3) the reference drop and rebound (both 80% of the jumping height of the maximal SJ) height condition (DJ_{ref}).

In each trial, the subject was pulled up to the predetermined dropping height. He then performed unilateral sledge jumps to the predetermined rebound height in a random order. The sledge seat displacements were confirmed by on-line monitoring immediately after each trial. The jumps were accepted if the rebound height was within ±2% of the target rebound height. One successful trial was required for each task. Two to three minutes were allowed between trials. The subjects were well practiced with all the testing conditions and none of them needed more than three trials for each task.

2.2. Measured parameters

Reaction forces (F_z, perpendicular to the movement plane of the sledge seat) were collected during the contact phase. Simultaneously, the position of the sledge seat was

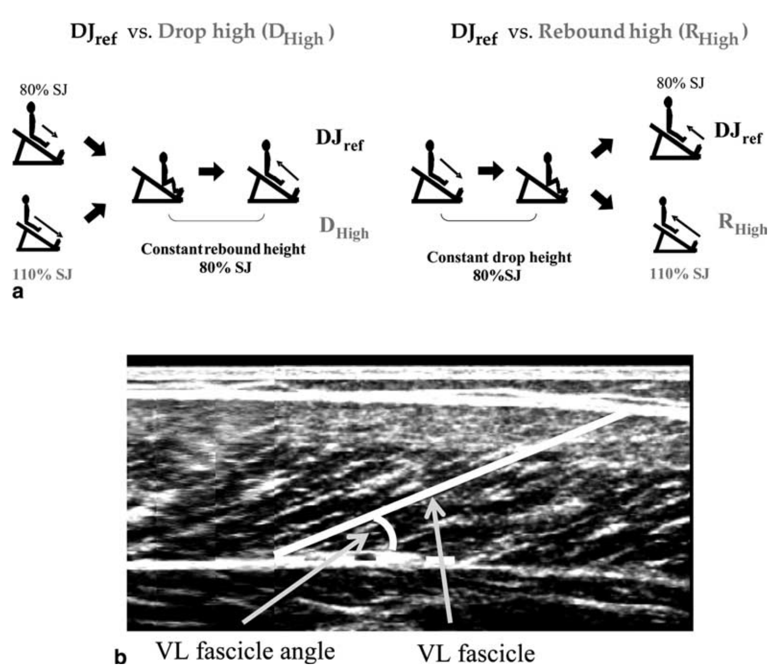

Fig. 1. (a) Schematic presentation of the experimental protocol. (b) The entire fascicle length of the vastus lateralis muscle (L_{fa}) was calculated as a linear continuation of the aponeuroses. The angle between the fascicle and the deep aponeurosis was defined as a fascicle angle.

measured to define the braking and push-off phases from the inflection point of the sledge position curve. The sledge apparatus has been explained in detail previously [6,27].

All the trials were video-recorded (200 fields s^{-1}) from the right side perpendicular to the line of motion. Video records were used to calculate the joint angles of the lower limb (hip, knee and ankle). The reflective markers placed on the right leg over the fifth metatarsal joint, tip of the lateral malleolus, distal epicondyle of the femur, great trochanter, and side of the neck at the level of the fifth cervical vertebra were digitized. The coordinates were filtered digitally through a butterworth 4th-order zero-lag low-pass filter (cut-off frequency 8 Hz).

Surface electromyographic (EMG) activity from vastus lateralis muscle (VL) of the right leg was recorded using miniature surface bipolar electrodes (Beckman skin electrode 650437, USA, input impedance >25 MΩ, common mode rejection ratio >90 dB) with an interelectrode distance of 20 mm according to the recommendations of SENIAM [39]. Care was taken that the interelectrode resistance was below 5 kΩ. The amplified EMG signals were stored simultaneously with the F_z and sledge position signals. These signals were digitized by a 12-bit A/D converter with a sampling frequency of 1 kHz. The EMG signals were band-passs filtered (5–500 Hz), full-wave rectified and finally low-pass filtered at 50 Hz (Butterworth type 4th-order digital filter). The averaged EMG (aEMG) was calculated separately for the following three phases; pre-activation, braking and push-off phases. The pre-activation phase was defined as 100 ms preceding the force plate contact [33]. The braking and push-off phases were determined from the inflection point of the sledge seat position and further divided into two phases of equal length (BrakeI, BrakeII, PushI and PushII phases, respectively). This was done for detailed observation of the fascicle and TT length changes because they do not follow the muscle-tendon unit (MTU) length changes during dynamic human SSC movements [19,24,25,28].

2.3. Muscle fascicle and tendinous tissue (TT) lengths of VL

The model of Hawkins and Hull [21] was used to estimate the changes in VL muscle-tendon unit length (L_{MTU}) from the knee joint angles. Muscle fascicle length of VL was measured during the jumping exercises by using B-mode ultrasound scanning (7.5 MHz probe, 60 mm; Aloka SSD-2000, JAPAN). The probe was positioned at the mid-thigh after the visibility of the echoes from the fascicle interspaces during movement was confirmed. Longitudinal ultrasonic images of VL were scanned at 50 images s^{-1}. Assuming a linear continuation, the total VL fascicle length (L_{fa}) was digitized with Motus software (Peak Performance Technologies, USA) [16,24,25] (Fig. 1B). The parts of the fascicle that were not visible were estimated to make the calculation possible [16,18,24,25]. The error for estimating L_{fa} has been reported to be 2–7% [16,18,24]. The angle between the fascicle and the deep aponeurosis was defined as a fascicle angle. The fascicle length in the direction of the line of pull (L_{M}) and the length of the tendinous tissues (L_{TT}) were calculated with the following equations [19,24,35,36]:

$$L_M = L_{\mathrm{fa}} \times \cos\alpha,$$
$$L_{\mathrm{TT}} = L_{\mathrm{MTU}} - L_{\mathrm{fa}} \times \cos\alpha,$$

where α is the fascicle angle, L_{M} is the fascicle length in the direction of the line of pull.

An electronic pulse was used to synchronize the EMG, kinetic, kinematics and ultrasonography data.

The lengthening and shortening velocities of MTU, fascicle and TT were defined as negative and positive, respectively. Because the length changes in MTU, fascicle and TT do not occur simultaneously, they have different stretching and shortening phases.

2.4. In vivo force measurements

In order to get a more accurate estimate of the VL muscle force, one of the subjects volunteered for a direct in vivo measurement of the patella tendon loading under all the experimental conditions. Details of the optic fiber methodology have been described elsewhere [4,16,24,31]. Before the jumping measurement, an optic fiber force transducer was inserted with a 19-gauge needle through the subject's patella tendon at the knee angle of 120° on the custom-built knee extension machine [34]. After the needle was removed, the optic fiber signal was converted into patella tendon force (PTF) from the force levels of the isometric knee extension. This calibration procedure has been explained in detail in the previous articles [16–18,24]. The moment arms of the patella tendon were determined from radiographs taken with a contracted muscle at the knee angle of approximately 180°, 120°, 60° [40]. It was decided to use the PTF instead of the quadriceps tendon force because determination of the quadriceps moment arm was more susceptible to errors and the difference between the two tendon forces can in some cases be up to 10% [16,18]. The VL muscle-tendon force was deduced from the PTF similarly to Ichinose et al. [23]:

$$F_{\mathrm{VL}} = \mathrm{PTF} \times 0.34,$$

where F_{VL} is the VL muscle-tendon force and 34% is considered as a relative physiological cross-sectional area (PSCA) of VL to the total PSCA of the quadriceps femoris muscle [1].

2.5. Statistics

Mean (±SD) values were calculated for 10 subjects. The ANOVA for repeated measurements on one factor and post hoc least significant difference multiple comparisons were used to reveal the significant difference between $\mathrm{DJ}_{\mathrm{ref}}$, R_{High} and D_{High}. If the normality test failed, the one way Friedman repeated ANOVA on Ranks was used. The Pearson's correlation coefficient was used to show the relationship between variables. We considered $P < 0.05$ as a statistically significant difference.

3. Results

Fig. 2 shows the mean curves during the contact phase for F_z, EMG and length data (MTU, fascicle and TT) between DJ_{ref} and R_{High}. The peak F_z and average braking force slope of F_z (F_z_slope) did not show any significant difference between DJ_{ref} and R_{High} (Table 1). The VL EMG activities increased from the late braking phase to the take-off until the take-off moment (Fig. 2) in all subjects. Significantly higher aEMG values were observed during the BrakeII, PushI ($P < 0.01$) and PushII ($P < 0.05$) phases of R_{High} than those of DJ_{ref} (Fig. 3). The MTU length at the contact moment (DJ_{ref} 27.57 ± 1.49, R_{High} 27.92 ± 1.39 cm) and the peak MTU length did not show any statistically significant difference between DJ_{ref} and R_{High} (DJ_{ref} 31.17 ± 1.13, R_{High} 31.10 ± 1.21 cm). The fascicle lengthening was smaller in the late braking phase of R_{High} than of DJ_{ref} (Fig. 2) in all subjects. This was associated with greater EMG activities ($P < 0.01$, Fig. 3) and consequently greater TT stretching in R_{High} than in DJ_{ref} ($P < 0.05$, Table 1). In the following push-off phase, the TT shortening was greater in R_{High} than DJ_{ref} ($P < 0.05$). Especially, the clear TT recoil was observed during the end of the push-off phase in R_{High} (Fig. 2) in all subjects. Conversely, the fascicle shortening was smaller in R_{High} than in DJ_{ref} ($P < 0.05$, Table 1, Fig. 2), although the EMG activities were still higher in R_{High} than in DJ_{ref} during the push-off phase ($P < 0.01$, Fig. 3).

Fig. 4 shows the mean curves during the contact phase for F_z, EMG and length data in DJ_{ref} and D_{High}. The peak F_z and the F_z_slope were greater in D_{High} than in DJ_{ref} ($P < 0.05$ and $P < 0.01$, respectively, Table 1). The MTU length at the moment of touch down (DJ_{ref} 27.57 ± 1.49, D_{High} 27.75 ± 1.28 cm) and the peak MTU length (DJ_{ref} 31.17 ± 1.13, D_{High} 31.18 ± 1.10 cm) did not show significant differences between DJ_{ref} and D_{High}. In D_{High} as

Table 1
Measured and estimated variables between the different conditions ($N = 10$)

	Reference jump (DJ_{ref})[a]	Rebound high (R_{High})	Drop high (D_{High})
Drop speed ($m\ s^{-1}$)	1.71 ± 0.17	1.72 ± 0.19	1.78 ± 0.17**
Rebound speed ($m\ s^{-1}$)	1.80 ± 0.13	1.94 ± 0.14**	1.80 ± 0.19
Peak F_z (kN)	1.75 ± 0.25	1.82 ± 0.29	1.86 ± 0.26*
Averaged F_z slope ($N\ s^{-1}$)	4167 ± 1133	4389 ± 1290	4642 ± 1052**
Contact time (ms)	510 ± 51	482 ± 54**	477 ± 52**
Braking phase	261 ± 32	246 ± 35	241 ± 33**
Push-off phase	250 ± 19	237 ± 23**	237 ± 22*
Lengthening amplitude (cm)			
MTU	3.46 ± 0.78	3.42 ± 0.75	3.60 ± 0.75
TT	2.29 ± 0.83	2.48 ± 0.90*	2.57 ± 0.90*
Fascicles	2.08 ± 1.24	1.80 ± 0.99*	2.26 ± 1.13*
Shortening amplitude (cm)			
MTU	6.38 ± 0.82	6.75 ± 0.81*	6.39 ± 1.03
TT	3.75 ± 0.92	5.25 ± 1.42*	4.98 ± 1.06*
Fascicles	3.77 ± 1.01	2.85 ± 0.93*	2.76 ± 0.90*
The peak TT shortening velocity ($cm\ s^{-1}$)	24.7 ± 4.3	36.4 ± 6.7*	27.9 ± 7.4
Timing of peak TT shortening velocity (ms)	473 ± 52	470 ± 53	432 ± 54*

Values are expressed as means ± SD
*,** Significantly different from DJ_{ref} at $P < 0.05$ and 0.01, respectively.
[a] The reference jump denotes the condition, in which both the drop and subsequent rebound heights were the same (see also Fig. 1).

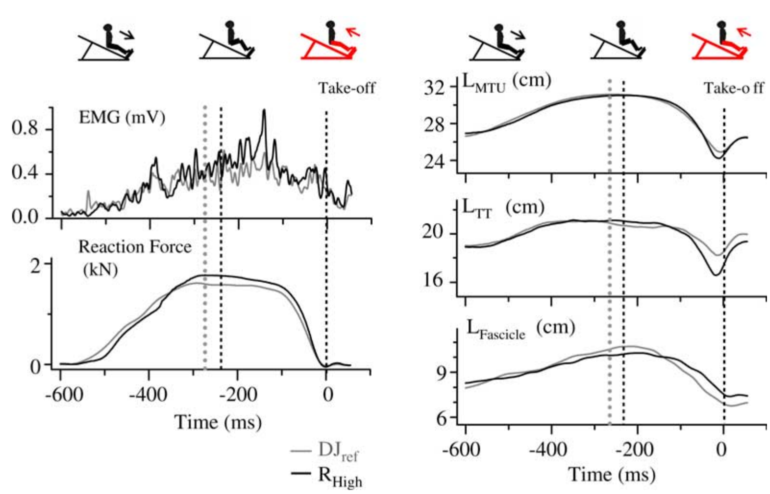

Fig. 2. The average curves ($N = 10$) of the rectified (and filtered) EMG activities (upper left), reaction force (lower left), and the lengths of the muscle-tendon unit (L_{MTU}, upper right), tendinous tissues (L_{TT}, middle right) and fascicle ($L_{fasiccle}$, bottom right) from the vastus lateralis (VL) muscle during the contact of the drop jumps (gray line, the control reference jump, DJ_{ref}; black line, the high rebound jump, R_{High}; dashed lines, standard deviation of each parameter). The vertical lines represent the transition between the braking and push-off phases (two first lines) and the moment of take-off (third line, $F_z = 0$).

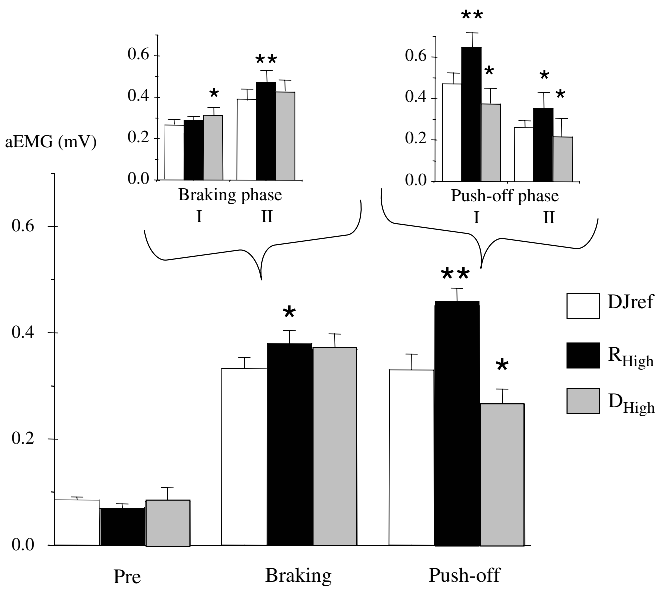

Fig. 3. Averaged EMGs (aEMG) of the Pre-activation (Pre), Braking (I, II) and Push-off (I, II) phases of the three different conditions of the sledge drop jumps. *,** Significantly different between DJ_{ref} and R_{High}, and DJ_{ref} and D_{High} at $P < 0.01$ and at $P < 0.05$, respectively.

compared to DJ_{ref}, a greater fascicle lengthening together with higher EMG activities and F_z_slope during the early braking phase was observed in all subjects (Fig. 4). But the fascicle length at the end of the braking phase did not show any significant difference (Fig. 4). During the subsequent early push-off phase, the fascicles in all subjects continued to lengthen. This is possible because of lower EMG activation in D_{High} than in DJ_{ref} (Fig. 4). Consequently, the fascicle was longer in D_{High} (8.06 ± 1.33 cm) than in DJ_{ref} (7.37 ± 1.26 cm) at the take-off moment ($P < 0.05$). The peak TT length (D_{High} 22.10 ± 1.67, DJ_{ref} 21.54 ± 1.56 cm) was greater ($P < 0.05$) and the TT length at the take-off moment (D_{High} 16.59 ± 1.43, DJ_{ref} 18.16 ± 1.85 cm) was shorter in D_{High} than in DJ_{ref} ($P < 0.05$). The aEMGs during the PushI and PushII phases were significantly smaller in D_{High} than in DJ_{ref} (Fig. 3). In this comparison, the TT shortening was greater in D_{High} than in DJ_{ref} ($P < 0.05$, Table 1), but the clear TT recoil during the end of the push-off phase was not observed in D_{High} in a similar way as that in R_{High}.

To examine these differences of the TT behavior, the TT shortening velocity was compared between conditions. The peak TT shortening velocity was significantly greater in R_{High} than in DJ_{ref} ($P < 0.05$) but was similar in D_{High} and DJ_{ref} (Table 1). The peak TT velocity took place earlier in D_{High} than in DJ_{ref} ($P < 0.05$) but did not show difference between D_{High} and DJ_{ref} (Table 1).

4. Discussion

We hypothesized that the increase in both drop and rebound intensities of SSC exercises modify the fascicle–TT interaction. The observed results confirm this suggestion and emphasize further that the elastic utilization in TT is different between the R_{High} and D_{High} conditions. The present results are in line with previous studies reporting greater TT shortening in both R_{High} and D_{High} as compared to DJ_{ref} [28,29]. Furthermore, the VL fascicles shortened less in both R_{High} and D_{High} as compared to DJ_{ref} during the push-off phase. However, the present results add information for the push-off phase that the EMG activation did not show a similar change in both R_{High} and D_{High} and enabled comparison of different mechanisms in elastic recoil.

4.1. Fascicle–TT interaction in different prestretch conditions

In D_{High}, due to the higher impact against the force plate, the slope of F_z development increased with a higher

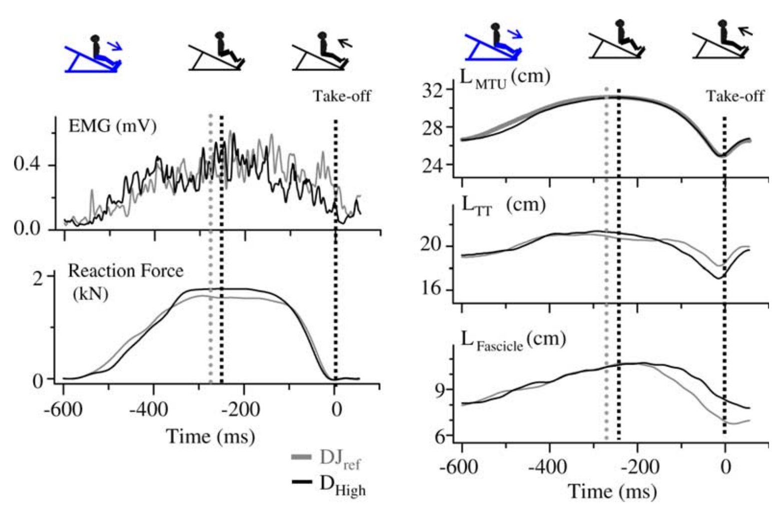

Fig. 4. The average curves ($N = 10$) of the rectified (and filtered) EMG activities (upper left), reaction force (lower left), and the length of the muscle-tendon unit (L_{MTU}, upper right), tendinous tissues (L_{TT}, middle right) and fascicle ($L_{fascicle}$, bottom right) from the vastus lateralis (VL) muscle during the contact phase (gray line, the control reference jump, DJ_{ref}; black line, the high drop jump, D_{High}; dashed lines, standard deviation of each parameter). The vertical lines represent the transition between the braking and push-off phases (two first lines) and the moment of take-off (third line, $F_z = 0$).

activation during the early braking phase. Consequently, TT can lengthen and store more energy in D_{High} than in DJ_{ref}. Indeed this was observed in the present study (Fig. 4). The TT underwent greater lengthening and shortening in D_{High} than in DJ_{ref}. The fascicles, on the other hand, lengthened more but shortened less in D_{High} than in DJ_{ref}. Fascicle lengthening, which continued in the early push-off phase, was associated with lower EMG activity during the entire push-off phase (Fig. 3). This fascicle lengthening during the push-off phase is in line with the concept of "timing of the muscle lengthening for effective release of elastic energy" by Ettema [14]. It suggests that the increased amount of stored elastic energy can be utilized effectively as the TT shortening is increased and the fascicle shortening reduced in D_{High}. This type of fascicle–TT interaction supports the concept of the "energy saving" mechanism as introduced by Cavagna [9] and Alexander and Bennet [2].

4.2. Fascicle–TT interaction in different rebound conditions

In R_{High}, the slope of the F_z development and the EMG activities did not show significant differences in the early braking phase because the drop height was the same as in DJ_{ref}. In the late braking phase, however, the greater EMG activation reduced the fascicle lengthening. In this condition, the TT was stretched more by the tension provided by fascicles and not by the impact ground reaction force. As suggested by Ettema and Huijing [15], the muscle length can affect the changes of the aponeurosis length but not the outer tendon length. In addition, the length changes in the outer tendon depend on the changes in the force level exerted on it. Based on their suggestion, the outer tendon may be stretched in a similar way between DJ_{ref} and R_{High} due to the similar F_z_slope. Instead, the greater stretch of aponeuroses can occur due to the higher EMG activation from the late braking phase in R_{High}. In the subsequent push-off phase, the EMG activity was higher in R_{High} than in DJ_{ref} but fascicle shortening was smaller in R_{High} and DJ_{ref}. Consequently, the timing of the peak TT shortening velocity was delayed in R_{High} as compared to DJ_{ref} due to the higher EMG activities. (The timing of peak TT shortening velocity was observed at the same time between R_{High} and DJ_{ref} but the total contact time was shorter in R_{High} than in DJ_{ref}; Table 1.) If the stretching and shortening of outer tendon behaved similarly between R_{High} and DJ_{ref}, the delayed timing of the peak TT shortening velocity may be due to behavior of the aponeuroses. This would mean that the observed greater TT stretch and recoil in R_{High} would occur in aponeuroses.

4.3. Process of utilization of elasticity

As discussed above, the TT stretch starts increasing from the late braking phase with increased rebound intensity. Its recoil becomes then greater in the late push-off phase (Fig. 2). Especially, aponeuroses may play an important role for stretching and shortening of TT. On the other hand, the outer tendon can stretch more in D_{High} than in DJ_{ref} from the early braking phase due to the increased F_z and F_z_slope. This different stretch timing in the different tendinous parts may affect the TT shortening during the push-off phase.

In order to understand the details of different TT shortening behavior under the controlled SSC conditions, the instantaneous force–velocity property of TT in the VL muscle was examined from one subject (Fig. 5). Although the peak VL tendon force during the contact phase did not show difference between the conditions, the enhancement process of VL tendon force and velocity was different. In R_{High}, VL tendon force and TT velocity enhancements were observed in the late shortening phase due to the higher TT shortening velocity, as shown by the shaded area (Fig. 5, left). In contrast, in D_{High}, the power output (VL tendon force × TT velocity) was enhanced during the early shortening phase due to the higher VL tendon force (Fig. 5,

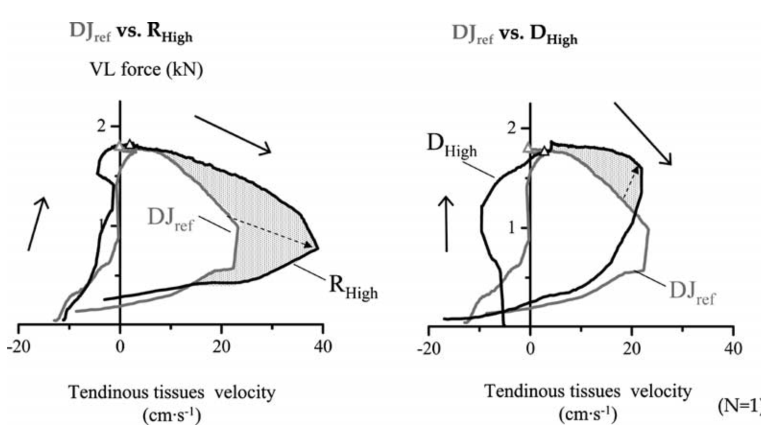

Fig. 5. Comparison of the instantaneous force–velocity (F–V) curves for the tendinous tissues from vastus lateralis (VL) during contact of three different conditions on the sledge drop jump for one subject. (Left, reference jump DJ_{ref} vs. high rebound jump R_{High}; Right, DJ_{ref} vs. high drop jump (D_{High})). Δ denotes the transition point from stretching to shortening in the muscle-tendon unit.

right). Incidentally, these enhancements in the push-off phase corresponded to the timing of the TT recoil (Table 1), as shown in Figs. 2 and 4.

In both D_{High} and R_{High}, the smaller lengthening of fascicles during the braking phase can support the concept of the ''concerted interaction'' by Hof et al. [22]. However, we propose an additional concept of the elastic energy utilization during SSC exercises. Based on the present results and literature, the modification of the fascicle–TT interaction during the varying intensity of the SSC can be formulated as follows (Fig. 6).

When the rebound height increased with a constant drop height (R_{High}), the slope of the reaction force and EMG activities did not show any difference as compared to DJ_{ref} in the early braking phase (Fig. 6B). Thereafter, the fascicles stretched less from the late braking phase with a higher EMG activation (Fig. 6C). In this situation, TT can be stretched more by the tension provided by fascicles. It can be speculated that when the prestretch intensity is the same, the interaction between fascicles and aponeuroses may be modified in response to the subsequent push-off intensity during SSC exercises. In the following push-off phase, the EMG activities were still higher with increasing rebound intensity, but the fascicle shortening did not increase (Fig. 6D). This longer fascicle length together with higher EMG activation at the higher rebound condition (R_{High}) indicates that the force on the fascicle level increased. Consequently, the rapid TT recoil was observed in the late push-off phase (Fig. 6E). This rapid TT recoil may have resulted from the shortening of the aponeuroses. Thus, it can be suggested that the outer tendon itself may not demonstrate the greater recoil in R_{High}. Instead we suggest that the aponeurosis can play an important role in this TT recoil as suggested by Alexander et al. [3] and Roberts et al. [38].

In contrast, when the drop height increased with a constant rebound height (D_{High}), due to the higher impact against the force plate, the slope of F_z development increased with higher activation during the early braking phase. Therefore, the outer tendon can be stretched more with increasing the drop intensity (Fig. 6F). Consequently, the TT shortening can start earlier and the power enhancement can be observed during the early push-off phase in D_{High} (Fig. 6H). In this condition, the rebound height was kept constant. During the early push-off phase, the fascicles still lengthened with less EMG activities. Consequently, the fascicle shortening decreased, but the TT shortening increased with increasing drop intensity (Fig. 6I).

It has been suggested that the storage and release of elastic energy could be associated not only with the prestretch speed but also with the short coupling time in SSC [7,10,30]. From the above discussion it can be speculated that the initial stretch increase due to the drop height gain and the smaller fascicle stretch due to the rebound height gain support their suggestions [7,10,13].

4.4. Methodological considerations

The sources of the experimental errors should be mentioned here. In the present study as in many other similar studies earlier, only one muscle (VL) was examined.

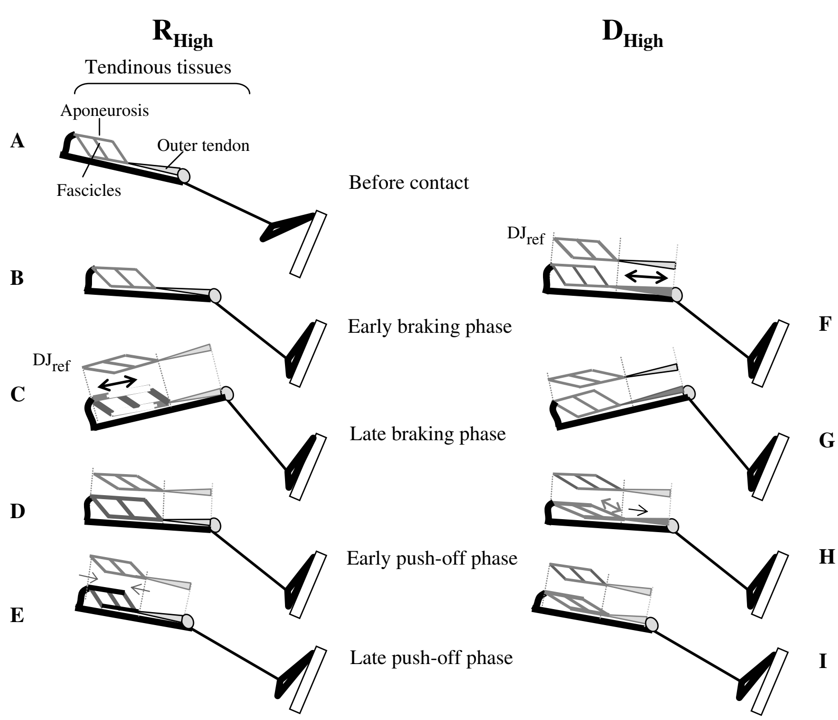

Fig. 6. Proposed schema of the modification of the VL fascicle–TT interaction during SSC exercises depending on the prestretch and rebound intensities. See text further explanation.

Second, can these results be interpreted to apply to all muscles of the ankle plantar flexion and knee extension involved in the present SSC exercises? According to the recent study [24] that compared the behavior of different muscles (VL and medial gastrocnemius) during SSC movements, it was shown that in both muscles the fascicles were stiffer with the increased rebound intensity and that TT recoil could be observable in both muscles. It is, therefore, suggested that with regard to TT behavior the present results can be interpreted to apply to other muscles during the SSC exercises. However, this suggestion needs to be verified in the future studies.

In summary, the present study using ultrasonography and in vivo tendon force measurement confirmed the hypothesis that there is an intensity specific fascicle–TT interaction to utilize the TT elasticity effectively during SSC exercises. Increase in dropping height can potentiate primarily the early push-off phase, whereas the increased rebound intensity provided the power enhancement during the late push-off phase. The present results suggest that the fascicle–TT interaction is modified depending on the drop and rebound intensities during SSC exercises. It remains unanswered, however, how the outer tendon and aponeuroses interact during SSC action.

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