

## Original Article

# Effects of External Load on the Contribution of Tendon Dynamics During Stretch-Shortening Cycle Exercises

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**Objectives:** This study aimed to determine the effect of external load on the contribution of tendon lengthening during eccentric phase and tendon shortening velocity during concentric phase in stretch-shortening cycle exercises. **Methods:** Fifteen men performed no-countermovement jump (noCMJ) and countermovement jump (CMJ) using only ankle joint with three different loads (0, 30, and 70% of 1 repetition maximum (RM)). Mean torque, angular velocity, power, and fascicle length of the medial gastrocnemius muscle were measured during jumping. In addition, the relative differences in the measured variables of CMJ compared to noCMJ were defined as pre-stretch augmentation. **Results:** During concentric phase, the pre-stretch augmentation in angular velocity and power was significantly correlated with that in tendon shortening velocity (except for 70% 1RM) but not in fascicle shortening velocity. The increases in tendon length during eccentric phase of CMJ were highly correlated with mean power during concentric phase for all load conditions. **Conclusion:** These results suggest that the tendon shortening velocity during concentric phase and the amount of tendon lengthening during eccentric phase (i.e., tendon dynamics) strongly contribute to increased performance in stretch-shortening exercises.

**Keywords:** Countermovement, Lengthening, Medial Gastrocnemius Muscle, Shortening, Ultrasonography

## Introduction

It is well known that stretching an activated muscle before shortening it improves its efficiency and performance during the concentric phase. To date, the mechanisms underlying a stretch induced enhancement have been controversial<sup>1,2</sup>. Among them, most previous studies have shown that the mechanical properties of tendons have positive effects on performance and efficiency during stretch-shortening cycle (SSC) exercises<sup>3-6</sup>. From simulation studies, it has been speculated that the mechanism of performance enhancement by the countermovement is the rapid shortening of tendons (known as concerted contraction

and catapult action<sup>7-9</sup>), which causes a decrease in the shortening velocity of muscle fibers, resulting in increased power (see Figure 9b in Hof et al.<sup>8</sup>). Furthermore, animal experiments *in vitro*<sup>10-13</sup> and human experiments *in vivo*<sup>14-18</sup> have demonstrated concerted contraction and catapult action-like muscle-tendon dynamics during SSC exercises. However, the effect of tendon shortening velocity during the concentric phase on performance improvement during SSC exercises has not been experimentally verified.

Theoretically, the greater the amount of tendon lengthening during the eccentric phase of SSC exercises, the higher the power during the concentric phase by storing more elastic energy in the tendon. Previous studies using electromyography demonstrated that the greater the stretch intensity (e.g., drop height in drop jump) during SSC exercise, the more elastic energy was utilized<sup>19,20</sup>. Indeed, it has been suggested that the higher the drop height in drop jump, the more significant the tendon lengthening during the eccentric phase and the more influential the contribution of tendon elasticity<sup>21,22</sup>. Therefore, those with greater tendon lengthening during the eccentric phase are expected to exert higher power in the subsequent concentric phase. Nevertheless, no studies have examined the effect of

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tendon dynamics during the eccentric phase of SSC exercise on performance during the subsequent concentric phase.

In actual sports competitions, the load (relative load) at which the required power is considered to differ depending on the sports discipline. For example, judo and wrestling require power under high load conditions, while boxing and karate require power under low load conditions. However, the influence of load on the contribution of tendon properties during SSC exercises has yet to be determined. On the other hand, according to previous studies using isolated animals and human cadavers<sup>23-25</sup>, the mechanical properties of tendons depend on their strain rate. Our recent studies also demonstrated that tendon lengthening was low and tendon hysteresis was high under conditions of high lengthening and shortening velocity of tendons<sup>26,27</sup>. Thus, under light load conditions, the contribution of tendon properties may be lower because of higher tendon lengthening and shortening velocities (i.e., smaller tendon lengthening and larger tendon hysteresis), and conversely, under heavy load conditions, the contribution of tendon properties may be higher.

In the present study, we aimed to examine the effect of external load on the contribution of tendon dynamics (tendon lengthening during the eccentric phase and tendon shortening velocity during the concentric phase) in SSC exercises. We hypothesized that the amount of tendon lengthening during the eccentric phase and the tendon shortening velocity during the concentric phase of the SSC exercises would contribute to the power during the concentric phase. In addition, these contributions would be more pronounced under higher load conditions.

## Materials and Methods

### Participants

Fifteen men (age:  $24.2 \pm 1.8$  yrs, height:  $174.5 \pm 4.8$  cm, body mass:  $69.4 \pm 9.2$  kg) voluntarily participated in the present study. Prior to the experiment, they had not participated in resistance training despite being physically active for at least a year. They were fully informed of the purpose of this study and the procedure that would be employed.

### Torque, angular velocity, and power during jumping

On a specially made sledge device (AO-3000K, Applied Office, Japan), participants performed unilateral jumps using only their right ankle joint under the following conditions: no-countermovement jump (noCMJ) and countermovement jump (CMJ) with three different loads (0, 30, and 70% of one repetition maximum (1RM)). The unilateral 1RM of the plantar flexor muscles was determined in all individuals at least one week prior to the assessments using a previously reported approach<sup>28</sup>. Using a digital high-speed camera (VCC-H1600C, Digimo, Tokyo, Japan), they were recorded during jumping test at a sampling rate of 250 Hz. On the right side of each participant,

four retroreflective markers were attached: the tip of the trochanter major, lateral epicondyle of the knee, lateral malleolus, and fifth metatarsophalangeal joint. The vertical reaction force during jumping was concurrently recorded from the force plate (Kistler, 9281B, Switzerland) attached to the platform of the sledge equipment.

Before testing, they performed several submaximal jumps to acquaint themselves with the test protocols. For each test, they were instructed to jump as high as they could. For noCMJ, they initially maintained the ankle in its most dorsiflexed position. Then they exerted plantar flexion torque until the toe lifted away from the surface of the force plate. For CMJ, they maintained in the maximal plantarflexed position, then exerted plantar flexion torque to the most dorsiflexed position and immediately rebounded to exert plantar flexion torque until the toe lifted away from the surface of the force plate. For each load condition, noCMJ measurements were performed first, followed by CMJ measurements.

For each condition, the test was repeated two times with a minimum of 1 min between tests. The order of tasks (0, 30, and 70% of 1RM) was randomized to avoid systematic effects. The ankle joint angle during jumping was analyzed using Motion Analysis Software (Frame-DIAS ver. 5, DKH, Tokyo, Japan). The ankle joint angle data was filtered using a fourth order Butterworth-type low-pass filter with a 15 Hz cutoff frequency. Using the procedure described by previous studies<sup>16,17,29</sup>, the ankle joint torque during jumping was calculated from the following equation:

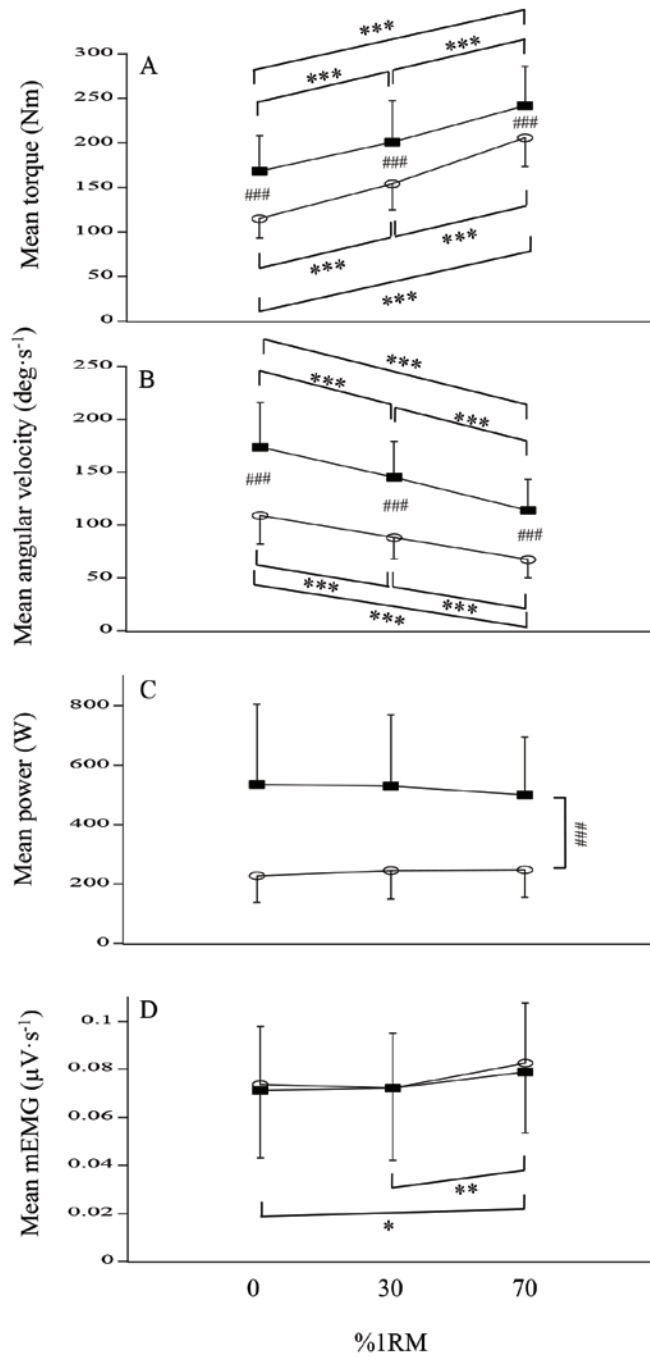
$$\text{Ankle joint torque} = F_z \cdot L \cdot \cos(A_j)$$

where  $F_z$ ,  $L$ , and  $A_j$  are the vertical reaction force, the length from the estimated center of the ankle joint to the ball of the foot, and the ankle joint angle. During the concentric phase, the duration, mean torque, mean angular velocity, and mean power were calculated. The mean values of two trials were used for the following analyses. The relative differences in mean torque, mean angular velocity, and mean power during the concentric phase of CMJ compared to noCMJ were defined as pre-stretch augmentation.

### Changes in fascicle and tendon length during jumping

During jumping, an ultrasonic apparatus (Prosound  $\alpha 7$ , Hitachi Aloka Medical, Tokyo, Japan) was used to measure the fascicle length ( $L_f$ ) and pennation angle of the medial gastrocnemius muscle (MG). At the proximal level of 30% of the lower leg length (i.e., from the popliteal crease to the center of the lateral malleolus), the scanning probe (7.5-MHz wave frequency with an 80-mm scanning length; UST 5713, Hitachi Aloka Medical, Tokyo, Japan) was secured using adhesive tape on the skin. Ultrasonic images were saved at 100 Hz in the computer memory of the apparatus. An electric signal was superimposed on the ultrasonic images to synchronize them with the other measured variables.

Using the procedure described by previous studies<sup>17,18,30,31</sup>, the lengths of muscle-tendon complex ( $L_{MTC}$ ) and tendon ( $L_T$ )



**Figure 1.** Mean torque (A), angular velocity (B), power (C), and mEMG (D) during the concentric phase of noCMJ (open) and CMJ (closed). Significant difference among the load levels: \* p<0.05, \*\* p<0.01, \*\*\* p<0.001. Significant between noCMJ and CMJ: ### p<0.001.

were calculated from the following equation:

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

$$L_T = L_{MTC} - L_F - \cos A_F^{-1}$$

where  $A_J$  and  $L_L$  are the ankle joint angle and the lower leg length.

#### Electromyographic activities during jumping

During jumping, electromyographic activities (EMG) of the lateral gastrocnemius muscle (LG) and soleus muscle (SOL) were recorded using a wireless telemetry device (BioLog DL-5500, S&ME, Japan) at a sampling rate of 1 kHz. EMG of

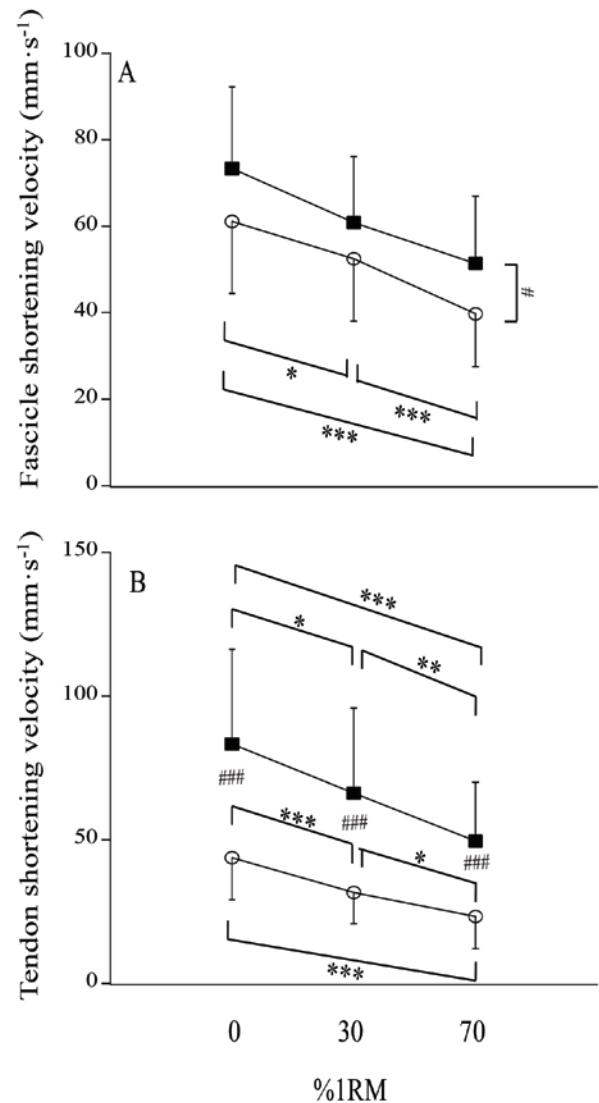
MG was not measured in order to obtain ultrasound images. Surface electrodes (DL-510, S&ME, Japan) were attached to the skin on the belly of each muscle. A band-pass filter was applied to the raw EMG data, ranging from 20 to 500 Hz. EMG amplitude was rectified and averaged (mEMG) during the eccentric phase (only CMJ) and the concentric phase. In addition, the averaged mEMG of LG and SOL was adopted as the mEMG of the plantar flexor muscles (PF). Similar to the pre-stretch augmentation in the measured variables (e.g., mean power), the relative difference in mEMG during the concentric phase of CMJ compared to noCMJ was calculated.

### Statistics

All data are presented as means  $\pm$  SD. The Shapiro-Wilk test was used to confirm that the measured variables had a normal distribution. For the changes in fascicle and tendon lengths during the eccentric phase of CMJ, an one-way analysis of variance (ANOVA) with repeated measures was used to detect significant differences among the load levels. Regarding the other measured variables, a two-way (mode  $\times$  load) ANOVA with repeated measures was employed to find significant differences in mode (noCMJ and CMJ) and load (%1RM). The F ratios for main effects and interactions were considered significant at  $p < 0.05$ . Significant differences among means at  $p < 0.05$  were detected using the Bonferroni post-hoc test. To assess the homogeneity of variance in each ANOVA, Mauchly's sphericity test was used. The Greenhouse-Geisser correction was used in cases when the sphericity assumption was violated. The effect size was calculated using partial eta-squared ( $p\eta^2$ ) for all ANOVAs. Based on the data distribution, Pearson's or Spearman's correlation coefficient was calculated to evaluate the correlations between the measured variables. The level of significance was set at  $p < 0.05$ .

### Results

There was no difference in the ankle joint angle at the lowest position among the three different loads for noCMJ ( $p = 0.382$   $p\eta^2 = 0.066$ ) and CMJ ( $p = 0.612$   $p\eta^2 = 0.035$ ). Mean torque, angular velocity, power, and mEMG during the concentric phase are shown in Figure 1. Regarding mean torque and angular velocity, the effect of the interaction between mode and load was significant ( $p = 0.001$   $p\eta^2 = 0.382$  for torque,  $p = 0.031$   $p\eta^2 = 0.255$  for angular velocity). For noCMJ and CMJ, mean torque increased significantly and angular velocity decreased significantly with increasing load. For all loads, mean torque and angular velocity for CMJ were significantly higher than those for noCMJ. Regarding mean power, the effect of mode was significant ( $p < 0.001$   $p\eta^2 = 0.768$ ), whereas the effects of load ( $p = 0.639$   $p\eta^2 = 0.019$ ) and the interaction between mode and load ( $p = 0.210$   $p\eta^2 = 0.110$ ) were not. Regarding mEMG, the effect of load was significant ( $p = 0.002$   $p\eta^2 = 0.370$ ), whereas the effects of mode ( $p = 0.356$   $p\eta^2 = 0.061$ ) and the interaction

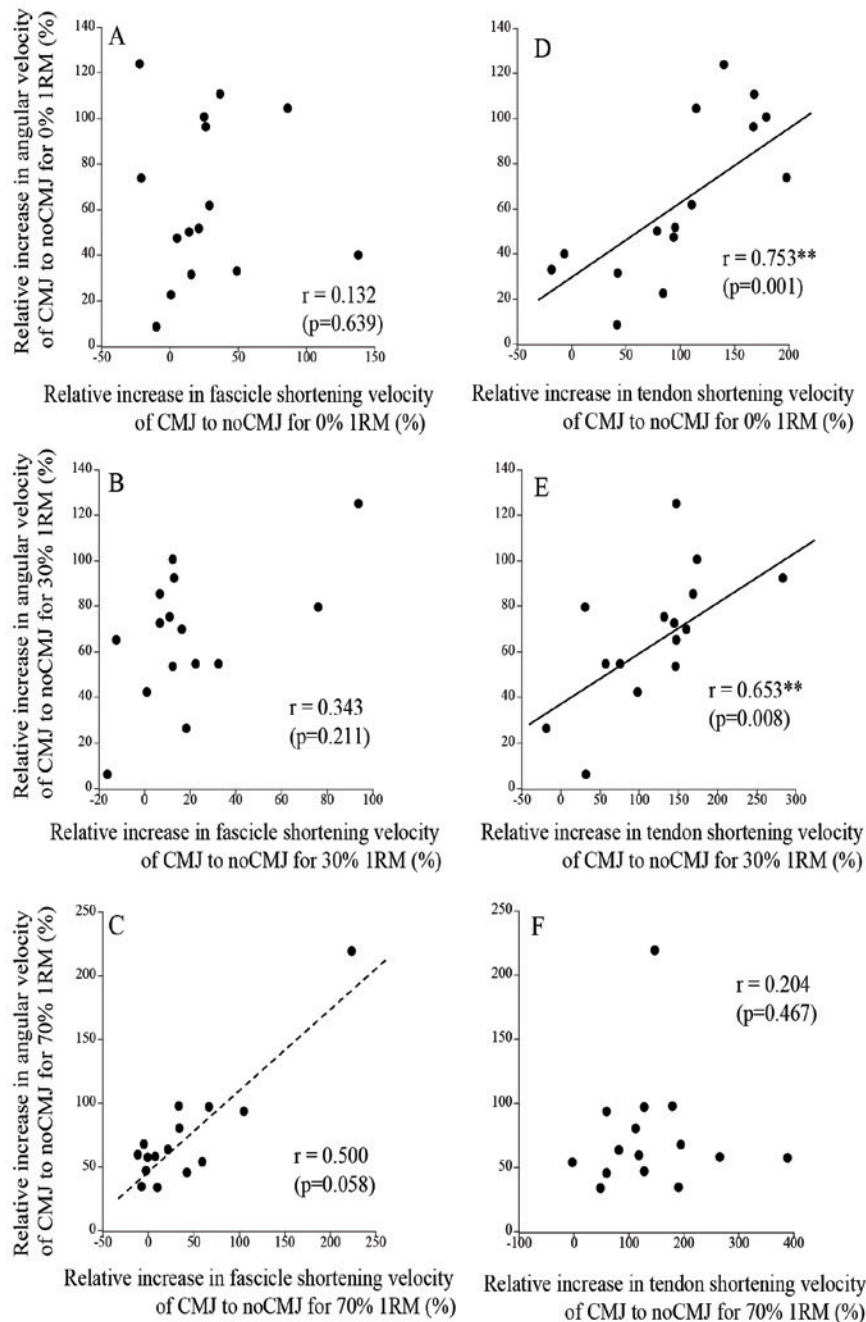


**Figure 2.** Shortening velocities of the fascicle (A) and tendon (B) during the concentric phase of noCMJ (open) and CMJ (closed). Significant difference among the load levels: \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ . Significant between noCMJ and CMJ: #  $p < 0.05$ , ###  $p < 0.001$ .

between mode and load ( $p = 0.727$   $p\eta^2 = 0.022$ ) were not.

The correlation coefficients between the pre-stretch augmentation in power and that in torque, angular velocity, and mEMG are shown in Table 1. The pre-stretch augmentation in power was significantly correlated with that in torque and angular velocity for all load conditions, with a particularly high correlation with the pre-stretch augmentation in angular velocity. However, pre-stretch augmentation in mEMG was not significantly correlated with that in power for all load conditions.

Mean shortening velocities of the fascicle and tendon



**Figure 3.** Relationships between the relative increase in angular velocity of CMJ to noCMJ and that in the shortening velocities of fascicle (A-C) and tendon (D-F). \*\*  $p < 0.01$ .

during the concentric phase are shown in Figure 2. Regarding fascicle shortening velocity, the effects of mode ( $p = 0.012$   $\eta^2 = 0.376$ ) and load ( $p < 0.001$   $\eta^2 = 0.734$ ) were significant, whereas the effect of the interaction between mode and load was not ( $p = 0.493$   $\eta^2 = 0.043$ ). Regarding tendon shortening velocity, the effect of the interaction between mode and load was significant ( $p = 0.026$   $\eta^2 = 0.22$ ). For noCMJ and CMJ, tendon shortening velocity

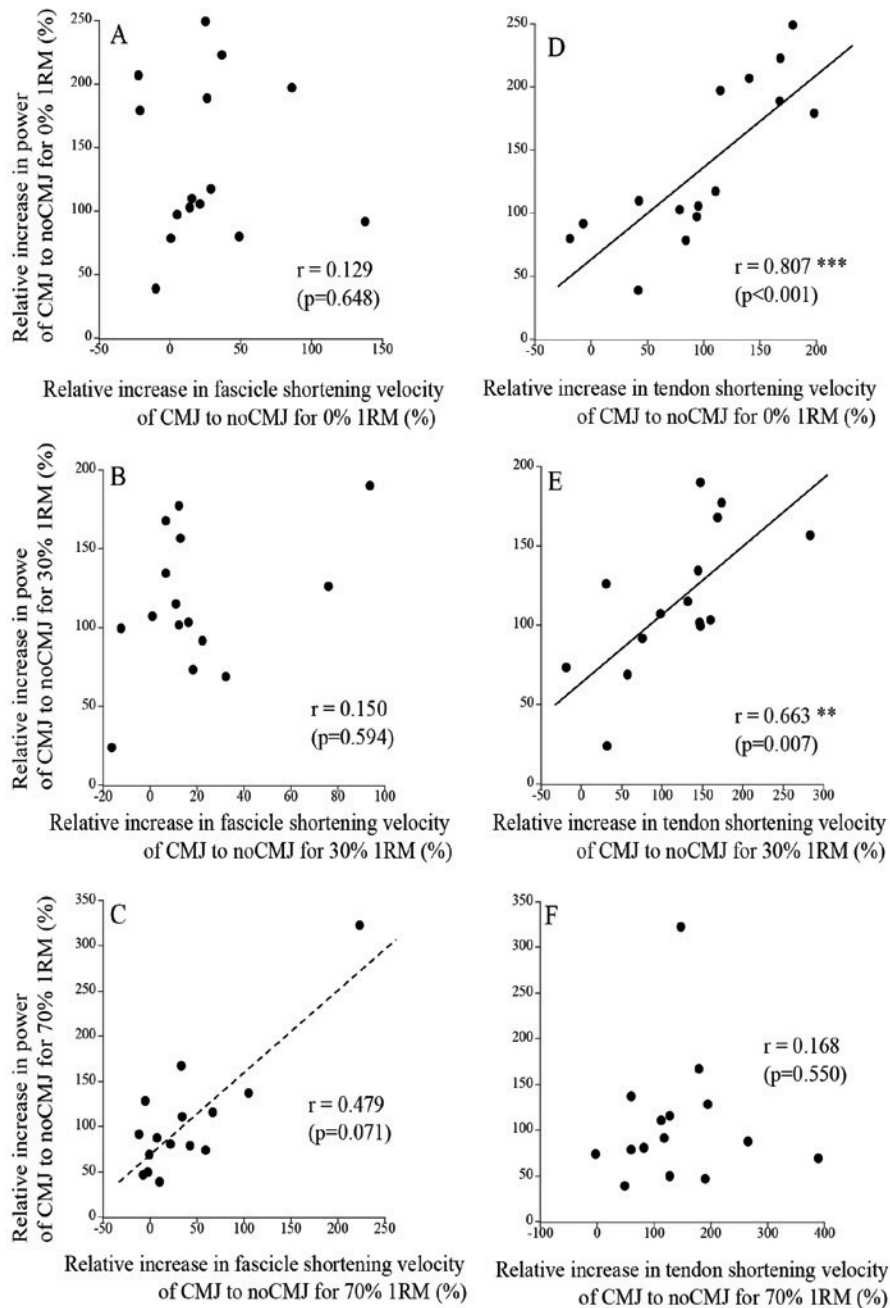
decreased significantly with increasing load. For all loads, tendon shortening velocity for CMJ was significantly higher than that for noCMJ. The difference in tendon shortening velocity between noCMJ and CMJ (2.2 times on average) was considerably greater than that in fascicle shortening velocity (1.3 times on average) and angular velocity (1.7 times on average).

The pre-stretch augmentation in angular velocity was

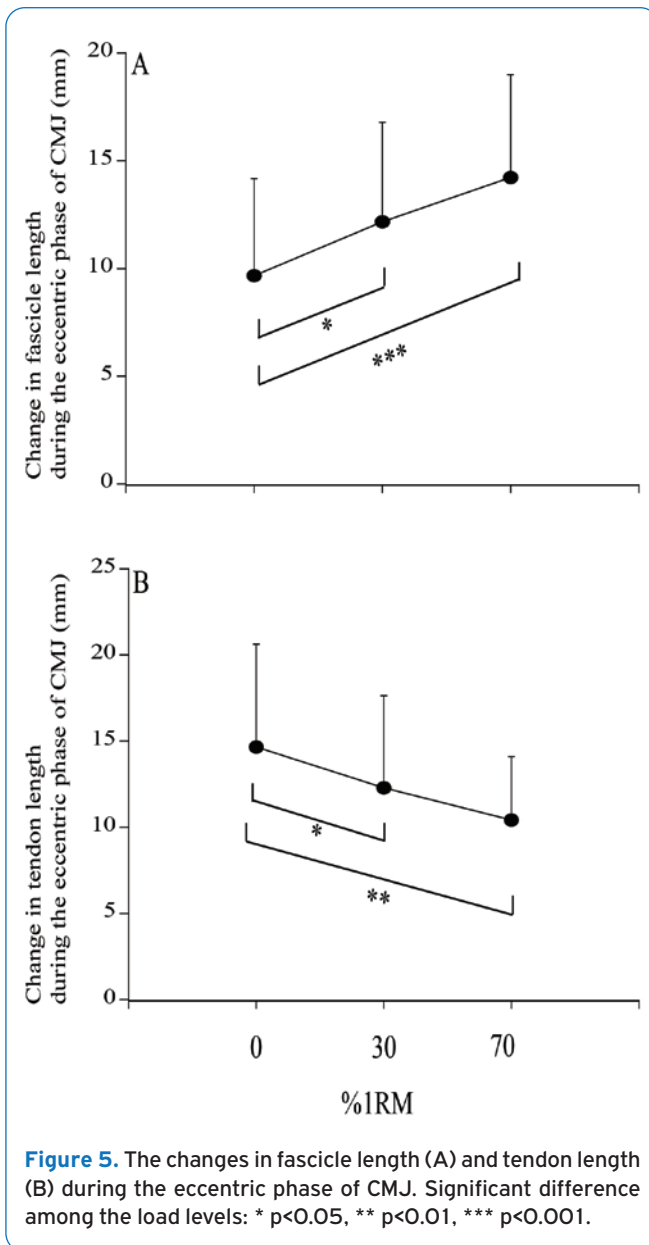
**Table 1.** Correlation coefficients between the pre-stretch augmentation in power and that in torque, angular velocity, and mEMG.

	0% 1RM	30% 1RM	70% 1RM
vs pre-stretch augmentation in torque	0.682 **	0.56 *	0.804 ***
vs pre-stretch augmentation in angular velocity	0.946 ***	0.932 ***	0.946 ***
vs pre-stretch augmentation in mEMG	0,115	0,217	0,379

\*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ .



**Figure 4.** Relationships between the relative increase in power of CMJ to noCMJ and that in the shortening velocities of fascicle (A-C) and tendon (D-F). \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$



significantly correlated with that in tendon shortening velocity (except for 70%1RM) but not in fascicle shortening velocity (Figure 3). Similarly, the pre-stretch augmentation in power was significantly correlated with that in tendon shortening velocity (except for 70%1RM) but not in fascicle shortening velocity (Figure 4). However, the correlation coefficients between the pre-stretch augmentation in fascicle shortening velocity and that in angular velocity and power tended to increase as the load increased (Figure 3 and 4).

During the eccentric phase of CMJ, the change in fascicle length significantly increased ( $p < 0.001$ ), and that in tendon length significantly decreased ( $p = 0.002$ ) as load increased (Figure 5). The increases in tendon length during the eccentric phase were highly correlated with mean power during the concentric phase for all load conditions, whereas the increase in fascicle length was significantly correlated with mean power for only 70% of 1RM (Table 2). No significant correlations between mEMG during the eccentric phase and mean power during the concentric phase were found for all load conditions (Table 2).

## Discussion

The main results of this study were that: 1) the pre-stretch augmentation in power during the concentric phase (i.e., relative increase in power of CMJ compared to noCMJ) was strongly associated with that in angular velocity (for all load conditions) and tendon shortening velocity (except for high load condition), 2) those with greater tendon lengthening during the eccentric phase of CMJ had greater power in the concentric phase for all load conditions.

Previous studies evaluated the recoil effect during SSC exercises regarding exerted power during the concentric phase and jump height<sup>4,32,33</sup>. These measured variables consist of force and velocity, but which factor contributes more significantly has yet to be examined. In this study, the increase in angular velocity of the CMJ relative to the noCMJ (1.7 times on average) exceeded the relative increase in torque (1.3 times on average). Furthermore, both “torque increase” and “angular velocity increase” were significantly correlated with the increase in power due to recoil, but the relationship with angular velocity tended to be more

**Table 2.** Correlation coefficients between the pre-stretch augmentation in power during the concentric phase and increases in fascicle and tendon lengths and mEMG during the eccentric phase of CMJ.

	0% 1RM	30% 1RM	70% 1RM
vs increase in fascicle length	0,432	0,201	0,686 **
vs increase in tendon length	0,889 ***	0,782 ***	0,763 ***
vs mEMG	0,454	0,361	0,370

\*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ .

robust (Table 1). To the best of our knowledge, for the first time, we showed that during SSC exercises, the increase in power was more strongly related to the increase in angular velocity than to the rise in force (or torque).

What, then, is the “increase in angular velocity” due to the recoil of SSC derived from? In the present study, fascicle and tendon shortening velocities, each constituting angular velocity, were calculated by measuring fascicle length changes. The difference in fascicle shortening velocity during the concentric phase between noCMJ and CMJ was slight, but the difference in tendon shortening velocity between noCMJ and CMJ was prominent (Figure 2). These results are consistent with those of several previous studies showing that the difference in fascicle shortening velocity during the concentric phase of jumps with and without countermovement was smaller than the difference in angular velocity<sup>16,29,34</sup>.

Under lower load conditions (0% and 30% of 1RM), the relative increases in angular velocity and power of CMJ compared to noCMJ were strongly correlated with the relative increase in tendon shortening velocity (Figures 3 and 4). According to the previous findings from simulation studies<sup>8,9</sup>, animal experiments<sup>10-13</sup>, and human experiments<sup>14-18</sup>, the rapid shortening velocity of tendons (i.e., catapult action) during the concentric phase of SSC exercises resulted in a lower shortening velocity of muscle fibers, which in turn increased exerted muscle strength and power. The present study directly demonstrated that the rapid shortening velocity of tendons during the concentric phase of SSC exercises was strongly related to increased angular velocity and power. At the beginning of this study, it was expected that these phenomena would be more pronounced under higher load conditions because the higher the shortening velocity of the tendon, the greater the tendon hysteresis<sup>26,27</sup>. However, our hypothesis was rejected. The reason of this discrepancy may be related to the fact that under higher load conditions, the fascicle is more stretched during the eccentric phase due to high load under 70% of 1RM condition (Figure 5). As a result, the amount of tendon lengthening may have been lower under high load condition. Conversely, under lower load conditions, fascicle elongation during the eccentric phase is likely to be smaller and tendon elongation is likely to be greater, resulting in a higher contribution to the reused elastic energy stored in the tendon during the subsequent concentric phase. In any case, it was shown experimentally for the first time that tendon shortening velocity contributed significantly to the increases in angular velocity and power of CMJ under lower load conditions. Several studies demonstrated that the relative work of tendons was greater under faster conditions during repetitive ankle bending exercises, hopping and running<sup>6,17,35,36</sup>. For example, Monte et al.<sup>36</sup> reported that with increasing running speed, the operating length of the MG fascicle shifted toward smaller lengths and the tendon lengthened more during stance phase. The present result supports the findings of these previous studies<sup>6,17,35,36</sup>.

In addition, during the eccentric phase, tendon

lengthening was greater under lower load conditions (Figure 5). Previous studies showed that higher drop height conditions in drop jumps resulted in greater tendon lengthening and less fascicle lengthening<sup>21,22</sup>. Based on the results of these studies, we expected higher load conditions to result in greater tendon lengthening and less fascicle lengthening during the eccentric phase. The result of this study, however, was quite the opposite. The mechanism for this result was unknown, but it may be that in the eccentric phase of CMJ, which requires more time than drop jump, the fascicles are lengthened more during the eccentric phase due to the load under high load conditions, resulting in less tendon lengthening. In any case, this result likewise supported the previous studies cited in the last paragraph, which showed an increased contribution of the tendon in fast SSC exercises. On the other hand, regardless of load conditions, those with greater tendon lengthening in the eccentric phase showed greater power in the concentric phase (Table 2). This result directly demonstrated that the degree of tendon lengthening in the eccentric phase of SSC exercises strongly influenced the performance of the subsequent concentric phase.

Under high load condition (70% of 1RM), the relative increases in angular velocity ( $p=0.058$ ) and power ( $p=0.071$ ) during the concentric phase of CMJ tended to correlate with the relative increase in fascicle shortening velocity but not tendon shortening velocity (Figure 3 and 4). As stated above, due to high load (70% of 1RM), the fascicles were stretched more during the eccentric phase of CMJ. Thus, the fascicle dynamics, rather than tendon dynamics, may contribute to power in the concentric phase under high load conditions. In addition, during the eccentric phase under high load condition (70% of 1RM), tendon lengthening and fascicle lengthening were significantly correlated with power during the concentric phase (Table 2), but unfortunately, the mechanism for this result is unknown.

We must discuss the limitations and underlying presumptions of the technique used in this study. Firstly, we measured fascicle lengths in MG only to examine the effect of load on the contribution of tendon dynamics during jumping. However, the gastrocnemius and soleus muscles differ significantly in terms of muscle fiber composition and muscle architecture<sup>37,38</sup>. In addition, the gastrocnemius muscles cross both the knee and ankle joints, whereas SOL crosses the ankle joint alone. Therefore, these differences between the gastrocnemius muscles and SOL may also relate to the fascicle-tendon dynamics of both muscles during exercise. Indeed, previous studies demonstrated that the fascicle dynamics of MG and SOL were different during multi-joint movements such as walking and drop jumps (with knee flexion)<sup>39,40</sup>. On the other hand, no difference in the behavior of MG and SOL was found during single joint movements such as isokinetic plantar flexion and ankle bending exercise<sup>41,42</sup>. Considering these points, we may say that there is no difference in fascicle-tendon dynamics between MG and SOL under the experimental

conditions employed in this study (jumping using only ankle joint). However, Hamard et al.<sup>15</sup> reported that the dynamics of MG and LG fascicles differed during SSC exercises. In the future, we must determine in a subsequent investigation if the behavior of MG is typical of all triceps surae muscles. Secondly, all participants in the present study were untrained men. According to the previous findings<sup>43,44</sup>, women and competitive athletes have different mechanical characteristics in their muscles and tendons compared to men who were not trained. Therefore, the results for women and athletes may differ from those of this study for untrained men.

The current findings indicate that the increase in tendon shortening velocity during the concentric phase and the amount of tendon lengthening during the eccentric phase contribute to the recoil effect (i.e., pre-stretch augmentation) of power in SSC exercises under lower load condition. These results suggest that tendon dynamics (shortening velocity and lengthening) contribute to increased performance in SSC exercises.

#### Ethics approval

*The present study was approved by the Ethics Committee for Human Experiments, Department of Life Science (Sports Sciences), The University of Tokyo (approval number: 882).*

#### Consent to participate

*Written informed consent was acquired from all the participants.*

#### Authors' contributions

*Takehiro Kosaka: performed experiments, analyzed data, prepared tables and figures, drafting the manuscript. Keitaro Kubo: conception of this study, interpreted results of experiments, drafting the manuscript. All authors read and approved the final version of manuscript.*

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