



Original Article

Effect of change in passive stiffness following low-intensity eccentric hamstring exercise on peak torque angle

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Abstract. [Purpose] The purpose of this study was to investigate the acute effect of low-intensity eccentric hamstring exercise on peak torque angle, range of motion, and passive stiffness. [Participants and Methods] Fourteen healthy young adults exercised as follows: 1) Under low-intensity eccentric hamstring exercise condition, participants performed a stiff-leg deadlift using a 20-kg barbell, 2) Under control condition with participants seated. The peak torque angle during eccentric knee flexion, hip flexion and knee extension range of motion, passive torque, and passive stiffness were measured before and after two conditions in the dominant leg. [Results] The low-intensity stiff-leg deadlift significantly increased hip flexion and knee extension range of motion and significantly decreased passive stiffness. Although the low-intensity stiff-leg deadlift did not change the peak torque angle, the changes in passive torque and passive stiffness were negatively correlated with the change in peak torque angle. [Conclusion] These results suggest that low-intensity eccentric hamstring exercise enhances flexibility, and a decrease in passive torque and passive stiffness are negatively associated with producing the eccentric peak knee flexion torque at a shorter muscle length.

Key words: Low-intensity eccentric hamstring exercise, Peak torque angle, Passive stiffness

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INTRODUCTION

Hamstring strain injury is a frequent non-contact injury in many sports¹⁾. In addition, hamstring strain injury has a high recurrence rate and causes the loss of playing time for athletes¹⁾. Furthermore, increasing age might be a risk factor for hamstring strain injury¹⁾; therefore, preventing hamstring strain injury is important for non-athletes and athletes.

There is increasing recognition that eccentric exercise at a longer muscle length potentially has an important role in preventing muscle strain injury, especially of the hamstring²⁾. Hamstrings contract eccentrically at a longer muscle length to absorb the hip flexion and knee extension moment in order to decrease the lower limb momentum during the late swing phase of sprinting³⁾. Thus, the hamstring is susceptible to acute muscle strain due to excessive force during sprinting⁴⁾. Of note, Brockett et al. reported that people with greater peak torque at a longer muscle length are less susceptible to severe muscle damage following eccentric contractions⁵⁾. Accordingly, enhancing hamstring muscle force at a longer muscle length by eccentric exercise might prevent hamstring strain injuries.

Acute eccentric hamstring contractions shift the peak torque angle to a longer muscle length (i.e., peak knee flexion

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torque is produced at a longer muscle length)^{5, 6}. Unfortunately, acute eccentric contractions also have an unfavorable effect on some risk factors for hamstring strain injury, such as range of motion (ROM), passive stiffness and muscle strength⁶. However, the degree of acute decrease in flexibility and muscle strength following the eccentric contractions might be due to the intensity of eccentric contraction⁷. Thus, low-intensity eccentric contractions might shift the peak torque angle to a longer muscle length with a minimum harmful effect for ROM, passive stiffness and muscle strength.

We previously reported that in participants with decreased hamstring flexibility, a single bout of low-intensity eccentric hamstring exercise without weight shifted the peak torque angle to a longer muscle length and increased ROM⁸. However, the acute effect of low-intensity eccentric hamstring exercise with weight on passive stiffness is still unclear. Accordingly, the aim of this study was to investigate the acute effect of low-intensity eccentric hamstring exercise with weight on the peak torque angle, ROM and passive stiffness. We hypothesized that low-intensity eccentric hamstring exercise improves the peak torque angle with a minimum harmful effect for ROM, passive stiffness and muscle strength.

PARTICIPANTS AND METHODS

Fourteen healthy male college students (mean \pm standard deviation: age, 24.4 \pm 2.3 years; height, 169.3 \pm 5.3 cm; body mass, 65.6 \pm 8.1 kg) voluntarily participated in this study. Exclusion criteria were a habit of lower limb resistance training and history of hamstring strain injuries. We previously reported that low-intensity eccentric hamstring exercise shifted the peak torque angle to a longer muscle length in subjects with decreased hamstring flexibility⁸. Therefore, the flexible participants who achieved more than 90° in the average baseline hip flexion ROM under two conditions were excluded based on a previous study's classification (tight [$<60^\circ$], normal [$60\text{--}90^\circ$], loose [$>90^\circ$])⁹. The current study was reviewed and approved by the institutional review board of the University of Tsukuba (approval number: 28-59), and conducted in conformity with the principles of the Declaration of Helsinki. All the study procedures and potential risks were explained to the participants, who provided written informed consent before study participation.

First, participants familiarized themselves with the measurements and procedure of low-intensity eccentric hamstring exercise with no resistance 3 days before the experimental session and the positioning of the dynamometer (e.g., the seat position, lever arm angle, and height) for each participant was determined. Second, participants conducted two experimental sessions with at least a 10-day rest interval. We set the following two conditions: 1) low-intensity eccentric hamstring exercise condition: participants performed low-intensity stiff-leg deadlift (SLDL) as an eccentric hamstring exercise (described below); and 2) control condition: participants were seated on a chair for 6 minutes. The order of the two conditions was randomly allocated. Before both experimental sessions, participants performed a 5-minute warm-up (60–70 rpm at 50 W) using a stationary bike (M3 Indoor Bike; Keiser Corp., Fresno, CA, USA). All variables of interest were measured before and after low-intensity eccentric hamstring exercise and the control condition.

Low-intensity SLDL procedure is showed in Fig. 1. Participants grasped a York Olympic barbell (20 kg) with their hands spaced slightly wider than their shoulder width. While maintaining a neutral spine position and very slightly flexed knees, the participants flexed their torso forward as far as comfortably possible¹⁰ for 5 seconds. The barbell was returned to the start position at each repetition by the investigator. Participants performed two sets of this exercise, each comprising eight repetitions, with 3 minutes of rest between sets.

Eccentric peak knee flexion torque and peak torque angle was measured using an isokinetic dynamometer (Biodex System 4; Biodex Corp., Shirley, NY, USA) while the participant was in a prone position with a neutral hip joint position (flexion angle of 0°). The upper back region and pelvis were secured to the seat of the device with Velcro straps. The axis of rotation of the dynamometer lever arm was aligned with the lateral epicondyle of the knee. The range of motion was set from the flexed position of 90° to 0° (0°=full knee extension). Angular velocity was set at 60°/s. Before the measurement, four submaximal

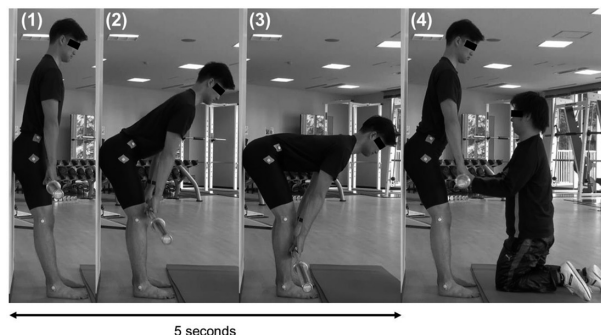


Fig. 1. Stiff-leg deadlift. Participants grasped a barbell with their hands spaced slightly wider than their shoulder width (1). While maintaining a neutral spine position and very slightly flexed knees, the participants flexed their torso forward as far as comfortably possible for 5 seconds (2–3). The barbell was returned to the start position at each repetition by the investigator (4).

and two maximal eccentric contractions were performed as a warm-up¹¹). Following the warm-up, participants performed three maximal voluntary eccentric knee flexions. The data analysis method was modified from the previous studies⁵). Torque values from isokinetic testing, which recorded more than 85% of peak knee flexion torque, were extracted and sorted according to the direction of movement and knee angle. These data were compressed using a decimation function that averaged every 10 successive data points and shown in the form of the active torque-angle curve. The eccentric peak knee flexion torque and peak torque angle were determined by this active torque-angle curve. We used the peak torque divided by body mass (kg) in the statistical analyses. In this study, smaller peak torque angle indicates that the peak knee flexion torque was produced at a longer muscle length.

The straight leg raise test was conducted to measure the hip flexion ROM (HF-ROM). The participants were in the supine position on an examination bed, and the pelvis and the non-tested leg were secured using straps. One investigator raised the participant's leg, with the participant's knee being passively extended, until the point which the participant feeling a strong but tolerable stretch, slightly before the occurrence of pain and another investigator measured the hip joint angle at this point by a goniometer.

Knee extension ROM (KE-ROM), passive torque and passive stiffness was calculated from the passive torque-angle curve using isokinetic dynamometer (Biodex System 3; Biodex Corp.). Participants were seated on an isokinetic dynamometer with both hip joints flexed 30° above the horizontal plane using the attachment for fixation, and the trunk was perpendicular to the horizontal plane by insertion of a wooden frame on the back side. The lateral epicondyle was aligned with the axis of the dynamometer. The knee joint was passively extended at 5 deg/s from the initial position (the knee flexed position of 90°) to the point of just before the onset of pain (endpoint), during which the passive torque was recorded to obtain a passive torque-angle curve¹²). KE-ROM was defined as the range from the initial position to the end point, and the passive torque at the endpoint was recorded. Passive stiffness was defined as the slope of the regression line calculated from the passive torque-angle curve above 50% of pre-KE-ROM using the least squares method. In post-measurement, passive torque and passive stiffness were calculated from pre-KE-ROM. However, if the post-KE-ROM was larger than that pre-KE-ROM, the angle range based on post-KE-ROM was used¹²). In this study, lower passive torque and passive stiffness indicate the higher flexibility.

All data are reported as a mean ± standard deviation. The Kolmogorov-Smirnov test was used to assess the normality of all parameters. Two-way analysis of variance (ANOVA) with repeated measures was used to identify the condition (low-intensity eccentric hamstring exercise or control) × time (before or after) interaction. When a significant interaction was identified, a post hoc t-test with Bonferroni correction was performed. Furthermore, the Spearman rank correlation coefficient was used to assess the correlations among the change in variables of interest. Statistical analyses were performed using SPSS (version 24). Statistical significance was set a priori at p<0.05.

RESULTS

Table 1 shows the variables of interest before and after the low-intensity eccentric hamstring exercise and control condition. According to the two-way ANOVA, a significant interaction effect (condition × time) was found for peak knee flexion torque ($F=12.95$, $p=0.003$), HF-ROM ($F=4.83$, $p=0.005$), KE-ROM ($F=12.03$, $p=0.004$) and passive stiffness ($F=5.4$,

Table 1. Variables of interest before and after the control and low-intensity eccentric hamstring exercise condition

Before		Before	After	ES (d)
Peak knee flexion torque (Nm/kg)	Control	1.43 ± 0.37	1.40 ± 0.32	0.08
	ECC-Ex	1.54 ± 0.24	1.29 ± 0.19*	1.13
Peak torque angle (°)	Control	17.3 ± 14.0	15.8 ± 14.0	0.10
	ECC-Ex	11.4 ± 10.2	11.8 ± 8.6	0.04
HF-ROM (°)	Control	75.5 ± 8.7	76.3 ± 11.0	0.08
	ECC-Ex	76.7 ± 10.0	81.9 ± 9.8*†	0.53
KE-ROM (°)	Control	79.4 ± 6.2	79.1 ± 7.5	0.05
	ECC-Ex	77.4 ± 8.7	82.1 ± 6.1*†	0.63
Passive torque (Nm)	Control	54.3 ± 11.0	55.3 ± 9.2	0.09
	ECC-Ex	53.5 ± 10.4	51.2 ± 12.2	0.20
Passive Stiffness (Nm/deg)	Control	0.86 ± 0.16	0.86 ± 0.10	0.03
	ECC-Ex	0.84 ± 0.13	0.78 ± 0.14*†	0.44

Value are mean ± SD. ECC-Ex: eccentric exercise; ROM: range of motion.

*p<0.05 vs. Before, †p<0.05 vs. Control.

Table 2. Correlation between the change in peak torque angle during eccentric knee flexion and change in other variables of interest in low-intensity eccentric hamstring exercise condition.

		Δ Peak knee flexion torque	Δ HF-ROM	Δ KE-ROM	Δ Passive torque	Δ Passive stiffness
Δ Peak torque angle	<i>r</i> value	-0.27	0.01	0.41	-0.58	-0.50
	<i>p</i> value	0.35	0.98	0.15	0.03	0.07

$p=0.04$). The post hoc t-test indicated that HF-ROM ($p=0.001$) and KE-ROM ($p=0.004$) were significantly increased, and peak knee flexion torque ($p<0.001$) and passive stiffness ($p=0.003$) were significantly decreased after the low-intensity eccentric hamstring exercise. Moreover, post value of HF-ROM and KE-ROM was larger for low-intensity eccentric exercise condition than control condition (HF-ROM, $p=0.02$; KE-ROM, $p=0.03$) and post value of passive stiffness was smaller for low-intensity eccentric exercise condition than control condition ($p=0.02$). The low-intensity SLDL did not change the peak torque angle during eccentric knee flexion; however, interestingly, change in the peak torque angle during eccentric knee flexion following the low-intensity SLDL significantly correlated with the change in passive torque ($r=-0.58$, $p=0.03$), and it tended to correlate with passive stiffness ($r=-0.50$, $p=0.07$) (Table 2).

DISCUSSION

The main findings of this study can be summarized as follows: low-intensity eccentric hamstring exercise increased ROM and decreased passive stiffness, whereas it decreased peak knee flexion torque. These results suggest that low-intensity eccentric hamstring exercise improved flexibility and decreased muscle strength. However, low-intensity eccentric hamstring exercise did not change the peak torque angle during eccentric knee flexion. Hence, our findings differed from our hypothesis. Interestingly, the change in passive torque and passive stiffness were negatively correlated with change in the peak torque angle during eccentric knee flexion.

To our knowledge, this is the first study to demonstrate an improvement of flexibility (i.e., an increase in ROM and decrease in passive stiffness) after a single bout of low-intensity eccentric hamstring exercise. These favorable changes may be induced by the SLDL. The SLDL was performed while maintaining very slightly flexed knees and flexing the torso forward as far as comfortably possible¹⁰; therefore, the SLDL can lengthen the hamstring to a longer muscle length. A degree of muscle elongation during the stretching seemed to be a crucial factor for the increase in flexibility¹³. Accordingly, larger hamstring elongation during the SLDL might be associated with an increase in flexibility. Larger hamstring elongation might affect the nervous system accommodation by Golgi tendon organs. Golgi tendon organs respond to the muscle fiber's tension and inhibit muscle contraction through the work of 1b afferents and the central nervous system. Moreover, Golgi tendon organs are most sensitive to tension forces generated by muscle contraction¹⁴, and the response of Golgi tendon organs is more enhanced as the muscle length and tension become greater¹⁵. The SLDL showed greater hamstring eccentric activity compared with other eccentric hamstring exercises, such as the gluteus-hamstring raise and prone leg curl¹⁶. Accordingly, it might be considered that the hamstring can work more eccentrically at a more muscle-lengthened position during the SLDL; as a result, Golgi tendon organs were enhanced and inhibited hamstring contraction, and the muscles became more flexible. In addition, the previous study reported that eccentric quadriceps exercise decreases the patellar tendon stiffness¹⁷ and eccentric triceps surae exercise improves the collagen fiber orientation of Achilles tendon¹⁸. Accordingly, increase in flexibility following low-intensity eccentric hamstring exercise might be due to these changes of the tendon property.

Interestingly, individual changes in passive torque and passive stiffness following low-intensity eccentric hamstring exercise were negatively correlated with changes in the peak torque angle during eccentric knee flexion, although it did not alter significantly presumably due to the large variability of individual changes. These results suggest that decreases in passive torque and passive stiffness are unfavorably associated with producing an eccentric peak knee flexion torque at a longer muscle length. Passive torque and passive stiffness are calculated based on passive tension¹⁹, which is produced by the series elastic element (e.g., the tendinous portion), and indicate the skeletal muscle viscoelasticity²⁰. As the skeletal muscle is further elongated, passive tension begins to contribute to the decrease of active tension, which is produced by the contractile element (muscle fiber), and allows producing large total muscle tension at a longer range of muscle lengths¹⁹. The skeletal muscle with lower passive torque and passive stiffness produce lower passive tension at a longer muscle length. Accordingly, the skeletal muscle with lower passive torque and passive stiffness could not produce the large total muscle tension at a longer muscle length. Furthermore, previous studies have advocated that the contractile element performs concentric and isometric actions, while the series elastic element is elongated during the eccentric contraction of skeletal muscles (e.g., the gastrocnemius²¹) and hamstring²²); thus, the series elastic element might have an important role in eccentric muscle contraction. Consequently, passive tension, which is produced by the series elastic element, could be associated with the force characteristic of the eccentric muscle contraction. Taken together, a decrease in total muscle tension due to the decrease in passive torque and passive stiffness might cause the deficit of eccentric knee flexion torque at a longer muscle length.

Our study demonstrated that the low-intensity eccentric hamstring exercise enhanced flexibility. However, the low-

intensity eccentric hamstring exercise also decreased eccentric peak knee flexion torque; hence, it is questionable whether it is better to perform the low-intensity eccentric hamstring exercise just before intense physical activity. Of note, the present study showed a negative correlation between change in the passive torque and passive stiffness, and change in the peak torque angle during eccentric knee flexion. Considering our results, in order to shift the peak torque angle during eccentric knee flexion to a longer muscle length, it might be necessary to increase the passive torque and passive stiffness. A previous study reported that plyometric exercise²³⁾ and isometric contraction²⁴⁾ increases passive stiffness. Therefore, examining the effect of plyometric exercise on the peak torque angle during eccentric knee flexion could be an interesting topic for future study.

Peak torque angle did not change significantly after the low-intensity eccentric hamstring exercise presumably due to the large variability of individual changes. The variability of individual peak torque angle changes might be related to the exercise intensity. In the present study, we used a 20-kg York Olympic barbell so this exercise could be easily performed in various clinical fields. However, since this load was not adjusted for each participant, it is considered that 20 kg was not an optimal load to improve the peak torque angle for any participants. Thus, we recommend that future study use a normalized intensity such as the percentage of maximum voluntary contraction and investigate the optimal intensity for individuals to shift the peak torque angle to a longer muscle length.

In conclusion, the present study demonstrated that low-intensity eccentric hamstring exercise increased the ROM and decreased the passive stiffness; thus, low-intensity eccentric hamstring exercise might be useful for improving flexibility. On the other hand, low-intensity eccentric hamstring exercise did not change the peak torque angle during eccentric knee flexion, but interestingly, the change in passive torque and passive stiffness were negatively associated with the change in peak torque angle during eccentric knee flexion. In order to shift the peak torque angle during eccentric knee flexion to a longer muscle length, it might be necessary to increase the passive torque and passive stiffness.

Conflict of interest

None.

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