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Research article

Acute Effects of Different Intensity and Duration of Static Stretching on the Muscle-Tendon Unit Stiffness of the Hamstrings

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Abstract
The effects of static stretching are influenced by prescribed and applied loads of stretching. The prescribed load is calculated from the stretching duration and intensity, whereas the applied load is assessed from the force of static stretching exerted on the targeted muscle. No previous study has investigated the prescribed and applied loads of static stretching on the muscle-tendon unit stiffness simultaneously. Therefore, the purpose of the present study was to examine the acute effects of the prescribed and applied load of static stretching on the change in the muscle-tendon unit stiffness of the hamstrings by using different intensities and durations of static stretching. Twenty-three participants underwent static stretching at the intensity of high (50 seconds, 3 sets), moderate (60 seconds, 3 sets), and low (75 seconds, 3 sets), in random order. The parameters were the range of motion, passive torque, and muscle-tendon unit stiffness. These parameters were measured before stretching, between sets, and immediately after stretching by using a dynamometer machine. The static stretching load was calculated from the passive torque during static stretching. The muscle-tendon unit stiffness decreased in high- and moderate-intensity after 50 ($p < 0.01$, $d = -0.73$) and 180 seconds ($p < 0.01$, $d = -1.10$) of stretching respectively, but there was no change in low-intensity stretching for 225 seconds ($p = 0.48$, $d = -0.18$). There were significant correlations between the static stretching load and relative change in the muscle-tendon unit stiffness in moderate- ($r = -0.64$, $p < 0.01$) and low-intensity ($r = -0.54$, $p < 0.01$), but not in high-intensity ($r = -0.16$, $p = 0.18$). High-intensity static stretching was effective for a decrease in the muscle-tendon unit stiffness even when the prescribed load of static stretching was unified. The applied load of static stretching was an important factor in decreasing the muscle-tendon unit stiffness in low- and moderate-intensity static stretching, but not in high-intensity stretching.

Key words: Static stretching load, intensity, duration, acute effect, muscle-tendon unit stiffness, range of motion.

Introduction

Static stretching is used as a common intervention in clinical (Costa and Vieira, 2008; Terada et al., 2013) and sports settings (Simenz et al., 2005; Takeuchi et al., 2019) to increase range of motion (ROM) and decrease muscle-tendon unit stiffness. Previous studies reported that high muscle-tendon unit stiffness is involved in the occurrence of muscle-tendon injuries (Watsford et al., 2010; Pickering et al., 2017). Therefore, it is important for athletes and clinicians to decrease muscle-tendon unit stiffness to prevent injuries.

The stress of static stretching is one important strategy for a decrease in the muscle-tendon unit stiffness of the hamstrings. The stress increases with stretching duration and intensity, and static stretching of longer duration (Ryan et al., 2009; Matsuo et al., 2013; Nakamura et al., 2019) or higher intensity (Kataura et al., 2017; Takeuchi and Nakamura, 2020a; 2020b; Takeuchi et al., 2021a; 2021c) effectively decreases the muscle-tendon unit stiffness. The stress of static stretching is assessed by using prescribed and applied loads of stretching. The prescribed load is calculated from the stretching duration and intensity (Freitas et al., 2014; Marchetti et al., 2019; Fukaya et al., 2020), and, for example, 240 seconds of static stretching at the intensity of 50% point of discomfort (POD) and 100 seconds of stretching at the intensity of 120%POD are considered as the same prescribed load (Fukaya et al., 2020). On the other hand, the applied load is assessed from the sum of the force of static stretching exerted on the targeted muscle by using a dynamometer machine (Takeuchi et al., 2021b). Previous studies examining the effective stretching intensity for decreasing the muscle-tendon unit stiffness of the hamstrings have not unified the prescribed load of static stretching. For example, Kataura et al. (2017) examined the effects of 180 seconds of static stretching at three different intensities (80%POD, 100%POD, and 120%POD intensities) and found that high-intensity static stretching was the most effective in decreasing the muscle-tendon unit stiffness of the hamstrings. When comparing the effects of different stretching intensities for the same duration, the prescribed load of static stretching is not unified, and as a result, high-intensity static stretching could have a higher effect on the decrease in the muscle-tendon unit stiffness. Therefore, the prescribed load of static stretching needs to be unified to clarify the effective stretching intensity in decreasing the muscle-tendon unit stiffness of the hamstrings.

The intensity of static stretching is determined based on ROM or POD of each participant, and 100%POD is a normal stretching intensity (Kataura et al., 2017; Takeuchi and Nakamura, 2020a; 2020b; Fukaya et al., 2020, 2021; Nakamura et al., 2021a; Takeuchi et al., 2021a; 2021c). Fukaya et al. (2020) unified the prescribed load of static stretching by comparing the effects of high-intensity with short-duration static stretching (120%POD intensity, 100 seconds) and low-intensity with long-duration static stretching (50%POD intensity, 240 seconds) and reported that high-intensity stretching was effective for decreasing the muscle stiffness of the gastrocnemius. However, they did not assess the applied load of static stretching (Fukaya et al., 2020). The applied load of static

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stretching of high-intensity with short-duration could be higher than that of low-intensity with long-duration because the force required for passive joint movement does not increase in approximately the first 50% of ROM, but it increases thereafter (Magnusson et al., 1996; Moltubakk et al., 2021).

Takeuchi et al. (2021b) calculated a static stretching load by using passive torque during static stretching to quantify the applied load of static stretching and found that the static stretching load was an important factor in decreasing the muscle-tendon unit stiffness of the hamstrings, regardless of stretching intensity. However, although the static stretching load is affected by both stretching intensity and duration, they only examined the effects of 60 seconds of two different intensities of static stretching (Takeuchi et al., 2021b). Moreover, they analyzed the static stretching load of 100%POD and 120%POD intensities together and did not investigate them independently. Therefore, it is necessary to examine the relationship between the static stretching load and changes in the muscle-tendon unit stiffness of the hamstrings for each stretching intensity and duration.

Previous studies reported that 180 seconds of static stretching at the intensity of 100%POD was needed to decrease the muscle-tendon unit stiffness of the hamstrings (Matsuo et al., 2013; Nakamura et al., 2019). To unify the prescribed load of static stretching in this study, we adjusted the stretching duration of 80%POD (3 sets of 75 seconds stretching) and 120%POD intensities (3 sets of 50 seconds stretching) based on 100%POD intensity (3 sets of 60 seconds of stretching). Therefore, the purpose of the present study was to examine the effects of the prescribed and applied loads of static stretching on the change in the muscle-tendon unit stiffness of the hamstrings.

Methods

Participants

Seventeen recreationally active men (19.8 ± 0.8 years, 172.8 ± 4.5 cm, 63.2 ± 5.8 kg) and six women (19.7 ± 0.5 years, 156.2 ± 4.1 cm, 49.5 ± 3.9 kg) participated in this study. Participants who were competitive athletes, who performed regular intensive stretching practice or strength training, or those who had a history of lower limb pathology were excluded. All participants were informed of the requirements and risks associated with their involvement in this study and signed a written informed consent document. The study was performed in accordance with the Declaration of Helsinki (1964). The Ethics Committee of Kobe International University approved the study (G2020-160).

Procedure

A randomized crossover trial was conducted. The participants visited the laboratory on separate days, with an interval of one week between visits. Participants attended a familiarization session one week before the first testing day. The participants underwent static stretching at low-intensity (80%POD), moderate-intensity (100%POD), and high-intensity (120%POD) of the hamstrings of the dominant limb (preferred leg when kicking a ball) (Nakamura et al., 2021a; Takeuchi et al., 2021b), in random order. Each static stretching intervention consisted of three sets of stretching. The knee extension ROM and passive torque at end ROM were measured before and immediately after the stretching intervention (Measurements 1 and 4) (Figure 1). The muscle-tendon unit stiffness was examined before stretching, between sets, and immediately after stretching (Measurements 1 - 4). The experiment was performed in a university laboratory, where the temperature was maintained at 25°C.

Sitting position

A flexibility assessment was performed in the same fashion as previous studies (Takeuchi and Nakamura, 2020a; 2020b; Takeuchi et al., 2021a; 2021b; 2021c). In the present study, an isokinetic dynamometer machine (CYBEX NORM, Humac, California, USA) was used. This study used a sitting position in which the hip joint was flexed, which has been shown to efficiently stretch the hamstrings (Kataura et al., 2017). The participants were seated on a chair with the seat tilted maximally, and a wedge-shaped wooden frame was inserted between the trunk and the backrest, which set the angle between the seat and the back at approximately 60 degrees. The chest, pelvis, and thigh were stabilized with straps. The knee joint was aligned with the axis of the rotation of the isokinetic dynamometer. The lever arm attachment was placed just proximal to the malleolus medialis and stabilized with straps. In the present study, reported knee angles were measured using the isokinetic dynamometer. A 90-degree angle between the lever arm and floor was defined as 0 degrees of knee flexion/extension. The participants were instructed to relax during the flexibility assessment.

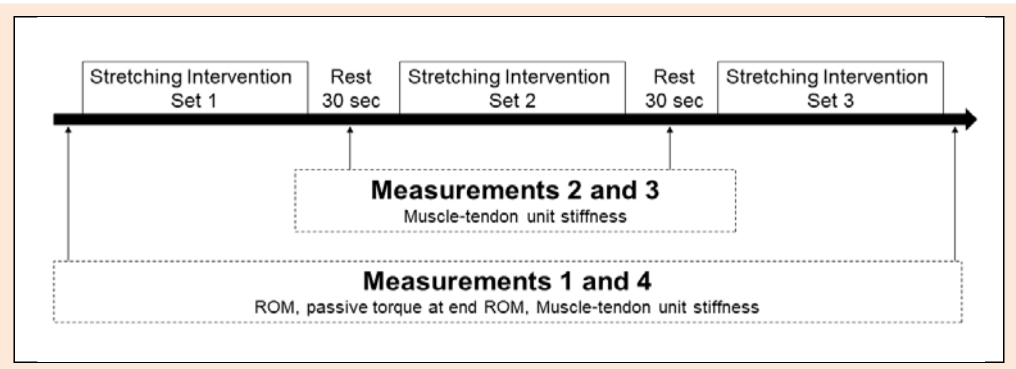

Figure 1. Experimental protocol. ROM: range of motion.

Knee extension ROM, passive torque at end ROM, and muscle-tendon unit stiffness

In Measurements 1 and 4, the knee joint was passively extended from 0 degrees to the maximum angle without pain. In Measurements 2 and 3, the knee joint was passively extended from 0 degrees to the maximum angle recorded in Measurement 1. The knee joint was passively moved at 5 degrees/second because the velocity does not cause a stretch reflex (Morse, 2011). The knee extension ROM was defined as the range from 0 degrees to the maximum knee extension angle without pain. The passive torque during the passive knee extension was recorded in the isokinetic dynamometer. After the experiment, the knee extension angle and passive torque during the flexibility measurement were exported to a personal computer, and the passive torque at end ROM and muscle-tendon unit stiffness were analyzed. The passive torque at the maximal knee extension angle (end ROM) was used for further analyses.

The muscle-tendon unit stiffness of the hamstrings was defined as the values of the slope of the regression line that was calculated from the torque-angle curve using the least-squares method (Magnusson et al., 1996; Magnusson, 1998; Kataura et al., 2017; Takeuchi and Nakamura, 2020a; 2020b; Takeuchi et al., 2021c). The muscle-tendon unit stiffness was calculated from the same knee extension angle range before and after static stretching. The calculated knee extension angle range was defined as the angle from the 50% maximum knee extension angle to the maximum knee extension angle measured in Measurement 1 (Magnusson et al., 1996; Magnusson, 1998; Kataura et al., 2017; Takeuchi and Nakamura, 2020a; 2020b; Takeuchi et al., 2021c). However, if the maximum knee extension angle measured after static stretching was smaller than that before stretching, the muscle-tendon unit stiffness was calculated from the 50% maximum knee extension angle to the maximum knee extension angle measured in Measurement 4.

Reliability of the measurements

The test-retest reliability was determined in 10 recreationally active participants (7 men and 3 women). The 2 tests were separated by one day and were performed at the same time of the day. The coefficient of variation of ROM, and passive torque at end ROM, and muscle tendon unit stiffness were 0.077, 0.385, and 0.315, respectively. The reliability of the knee extension ROM (intraclass correlation coefficient (ICC) of 0.98), passive torque at end ROM (ICC of 0.87), and muscle-tendon unit stiffness (ICC of 0.87) were acceptable in this study.

Static stretching

Static stretching was performed on the isokinetic dynamometer in the same fashion as the measurement of the knee extension ROM (Kataura et al., 2017; Takeuchi and Nakamura, 2020a; 2020b; Takeuchi et al., 2021a; 2021b). Static stretching was performed at three different intensities (80%POD, 100%POD, and 120%POD). For 80%POD, static stretching for a total of 225 seconds (75 seconds of stretching with 30 second rest intervals) at the intensity of 80%POD was performed. For 100%POD, static stretching for a total of 180 seconds (60 seconds of stretching with 30 second rest intervals) at the intensity of 100%POD was performed. For 120%POD, static stretching for a total of 150 seconds (50 seconds of stretching with 30 second rest intervals) was performed. The stretching intensity was determined based on the POD of each participant. At 100%POD intensity, the angle was set just prior to the POD (Kataura et al., 2017; Takeuchi and Nakamura, 2020a; 2020b; Takeuchi et al., 2021a; 2021b). At 80% and 120%POD intensities, the angle was set to 0.8 and 1.2 times the POD, respectively. The mean knee extension angles of 80%POD, 100%POD, and 120%POD intensities were 38.0 ± 8.2 degrees, 47.1 ± 11.1 degrees, and 47.1 ± 11.1 degrees, respectively. The participants were instructed to relax during each stretch.

Calculation of static stretching load

Passive torque during static stretching was recorded by the dynamometer and exported to the personal computer to analyze the static stretching load. The static stretching load was the sum of the passive torque per second during the static stretching of each set (Takeuchi et al., 2021b). To analyze the relationship between the static stretching load and relative changes in the knee extension ROM and passive torque at end ROM, the sum of the three sets of the static stretching load was used. In addition, the relationship between relative changes in the muscle-tendon unit stiffness of Measurements 2, 3, and 4 and the static stretching load of Set 1, the sum of Sets 1 and 2, and the sum of Sets 1, 2, and 3 were analyzed, respectively.

Statistical analyses

The statistical analyses were performed according to previous studies (Takeuchi and Nakamura, 2020a; 2020b). Analyses were performed using SPSS version 25 (SPSS, Inc., Chicago, IL, USA). The normal distribution of the data was confirmed using the Shapiro-Wilk test. All variables except the static stretching load was represented as mean ± standard deviation. The static stretching load was described as a median (interquartile range). The statistical power was calculated from the effect size of the muscle-tendon unit stiffness, which was the main outcome of this study, using G*power at a setting of $\alpha = 0.05$ and sample size of 23 (Takeuchi and Nakamura, 2020a). The results indicated that the statistical power was 1.00. A two-way repeated measures ANOVA (intervention [80%POD vs. 100%POD vs. 120%POD] and time [Measurement 1 vs. Measurement 4]) was used to analyze the knee extension ROM and passive torque at end ROM data. A two-way repeated measures ANOVA (intervention [80%POD vs. 100%POD vs. 120%POD] and time [Measurement 1 vs. Measurement 2 vs. Measurement 3 vs. Measurement 4]) was used to examine the muscle-tendon unit stiffness data. If a significance was detected, post hoc analyses using Bonferroni's test were performed to determine where significant differences occurred. Effect sizes were calculated as the mean difference between Measurements 1 and Measurements 2, 3, and 4 divided by the pooled standard deviation. Pearson's correlation coefficient was conducted between the static stretching load and relative changes of the knee extension ROM, passive torque at end ROM, and muscle-tendon unit stiffness. Differences were considered statistically significant at an alpha of 0.05.

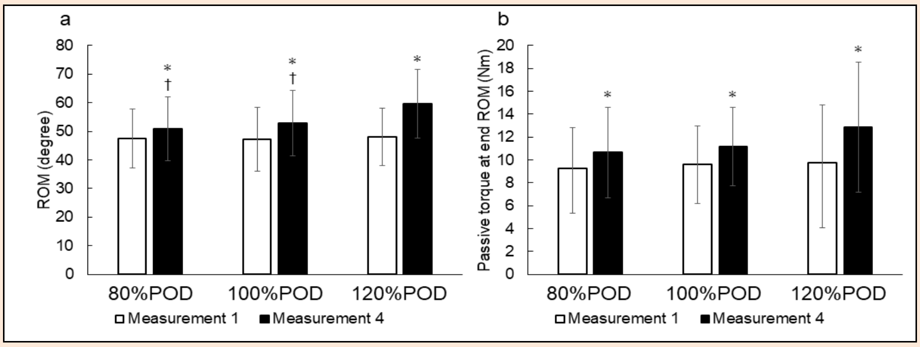

Figure 2. Changes in knee extension range of motion (ROM) (a) and passive torque at end ROM (b). Data were represented as mean ± standard deviation. * p < 0.01 vs. value in the same intervention in Measurement 1. † p < 0.01 vs. value at 120%POD in Measurement 4. POD: point of discomfort.

Results

Knee extension ROM, passive torque at end ROM

For the knee extension ROM, there was a significant two-way interaction (intervention × time, $p < 0.01$, $F = 56.6$, partial eta squared = 0.73) (Figure 2). The knee extension ROM increased in all interventions (80%POD, $p < 0.01$, d = 0.31; 100%POD, $p < 0.01$, d = 0.51; 120%POD, $p < 0.01$, d = 1.04). In Measurement 1, there was no significant difference between interventions (all p = 1.00). In Measurement 4, the knee extension ROM at 120%POD was significantly higher than that at 80%POD ($p < 0.01$) and 100%POD ($p < 0.01$), but there was no significant difference between 80%POD and 100%POD (p = 0.52).

For the passive torque at end ROM, there was a significant two-way interaction (intervention × time, p = 0.02, F = 4.4, partial eta squared = 0.17). The passive torque at end ROM increased in all interventions (80%POD, $p < 0.01$, d = 0.36; 100%POD, $p < 0.01$, d = 46; 120%POD, $p < 0.01$, d = 0.58). There was no significant difference between interventions in Measurement 1 (all p = 1.00) and 4 (80%POD vs 100%POD, p = 1.00; 80%POD vs 120%POD, p = 0.21; 100%POD vs 120%POD, p = 0.39).

Muscle-tendon unit stiffness

There was a significant two-way interaction (intervention × time, $p < 0.01$, F = 13.4, partial eta squared = 0.38) (Figure 3). At 80%POD, there was no significant difference between Measurement 1 and Measurements 2 (p = 0.56, d = 0.11), 3 (p = 1.00, d = -0.03), and 4 (p = 0.48, d = -0.18). At 100%POD, there was no significant difference between measurement 1 and 2 (p = 1.00, d = -0.12) and 3 (p = 0.11, d = -0.26), but measurement 4 was significantly lower than that of measurement 1 ($p < 0.01$, d = -0.73). At 120%POD, the muscle-tendon unit stiffness in Measurements 2 ($p < 0.01$, d = -0.71), 3 ($p < 0.01$, d = -0.99), and 4 ($p < 0.01$, d = -1.10) were significantly lower than that in Measurement 1. In addition, at 120%POD, the muscle-tendon unit stiffness in Measurements 2 (80%POD, p = 0.04; 100%POD, p = 0.01), 3 (80%POD, $p < 0.01$; 100%POD, $p < 0.01$), and 4 (80%POD, p = 0.02; 100%POD, $p < 0.01$) were significantly lower than that at 80%POD and 100%POD at the same time.

Static stretching load

There was a significant two-way interaction (intervention × time, $p < 0.01$, F = 5.6, partial eta squared = 0.20) (Table 1). At 80%POD and 100%POD, there was no significant difference between sets. On the other hand, at 120%POD, Set 1 was significantly higher than Sets 2 ($p < 0.01$) and 3 ($p < 0.01$), and Set 2 was significantly higher than Set 3 (p = 0.02). The static stretching load at 120%POD was significantly higher than that at 80%POD and 100%POD ($p < 0.01$), and at 100%POD it was significantly higher than that at 80%POD ($p < 0.01$).

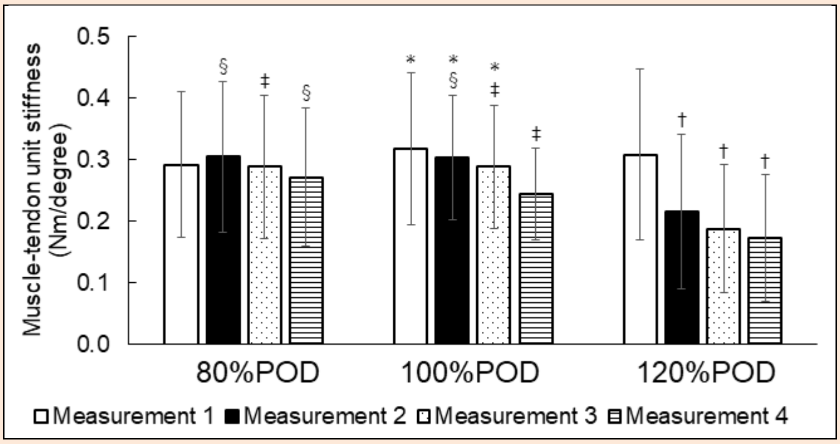

Figure 3. Change in muscle-tendon unit stiffness. Data were represented as mean ± standard deviation. * p < 0.01 vs. value at 100%POD in Measurement 4. † p < 0.01 vs. value at 120%POD in Measurement 1. ‡ p < 0.01 vs. value at 120%POD at same time. $ p < 0.05 vs. value at 120%POD at the same time. POD: point of discomfort.

Table 1. Static stretching load of each intervention.

	Set 1 (Nm)	Set 2 (Nm)	Set 3 (Nm)
80%POD	213.5 (108.8 - 605.0)	203.7 (90.3 - 678.4)	210.6 (38.4 - 648.5)
100%POD	404.2* (259.0 - 609.9)	360.6* (258.7 - 610.5)	400.2* (239.0 - 525.0)
120%POD	698.3*, † (594.5 - 1473.6)	567.9*, †, ‡ (458.2 - 1234.8)	552.2*, †, ‡, $ (406.6 - 1150.1)

Data were represented as median (interquartile range). * $p < 0.01$ vs. value at 80%POD at the same time. † $p < 0.01$ vs. value at 100%POD at the same time. ‡ $p < 0.01$ vs. value at 120%POD in Set 1. $ $p < 0.05$ vs. value at 120%POD in Set 2. POD: point of discomfort.

Correlations between the static stretching load and measurements of flexibility

There was a significant correlation between the static stretching load and relative change in the knee extension ROM ($r = 0.52$, $p < 0.01$), but there was no significant correlation between the static stretching load and relative change in the passive torque at end ROM ($r = 0.08$, $p = 0.53$).

There were significant correlations between the static stretching load and relative change in the muscle-tendon unit stiffness at 80%POD ($r = -0.54$, $p < 0.01$), 100%POD ($r = -0.64$, $p < 0.01$), and all interventions ($r = -0.57$, $p < 0.01$) (Figure 4). However, there was no significant correlation between the static stretching load and relative change in the muscle-tendon unit stiffness at 120%POD ($r = -0.16$, $p = 0.18$).

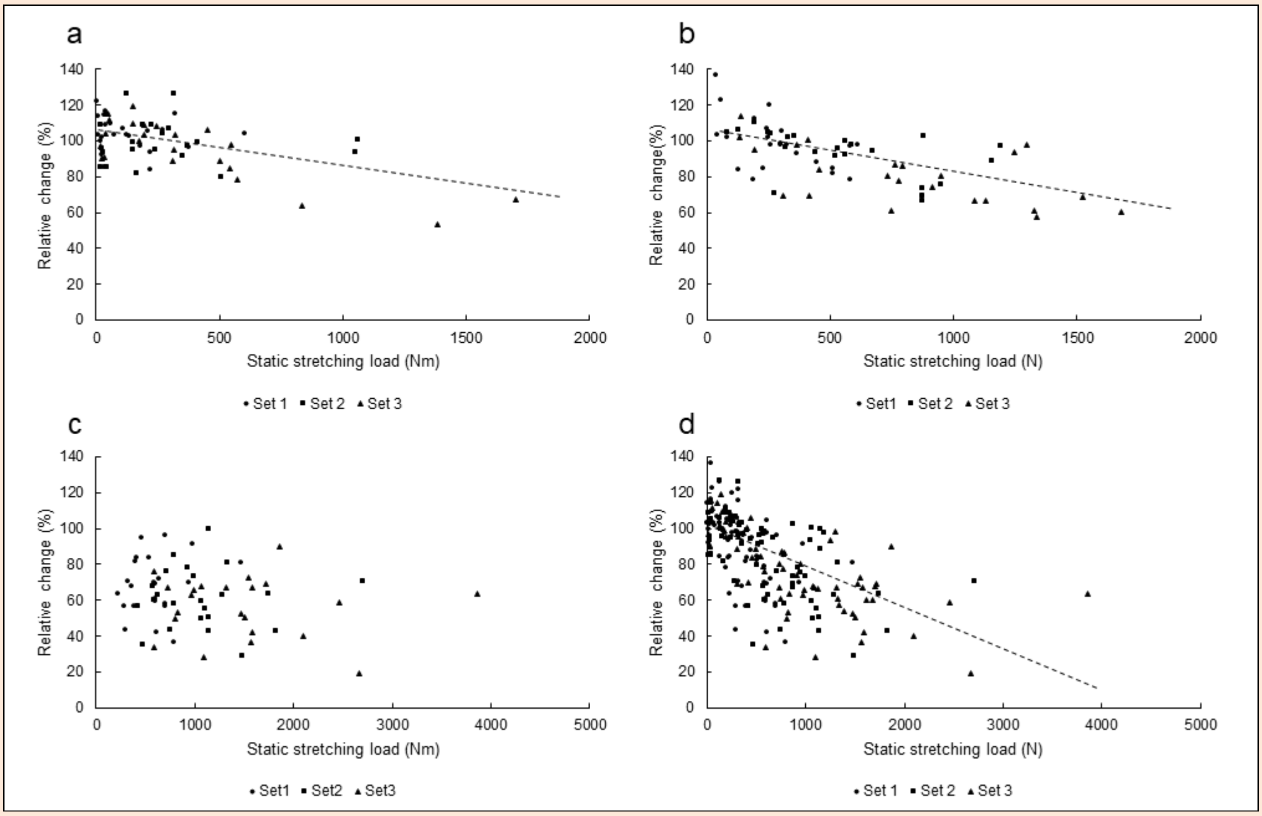

Figure 4. Correlation between static stretching load and relative changes in muscle-tendon unit stiffness at 80%POD (a), 100%POD (b), 120%POD (c), and all interventions (d). POD: point of discomfort.

Discussion

Previous studies reported that high-intensity static stretching was more effective for an acute increase in the knee extension ROM and a decrease in the muscle-tendon unit stiffness of the hamstrings compared with moderate- and low-intensity static stretching (Kataura et al., 2017; Takeuchi and Nakamura, 2020a; Fukaya et al., 2021; Takeuchi et al., 2021a; 2021b; 2021c), although these previous studies did not unify the prescribed load of static stretching. In this study, the prescribed loads of low-, moderate-, and high-intensity static stretching were unified by adjusting the stretching duration based on moderate-intensity static stretching. The results of the present study showed that high-intensity static stretching for 150 seconds was the most effective for an increase in knee extension ROM and a decrease in the muscle-tendon unit stiffness of the hamstrings. On the other hand, the passive torque at end ROM increased in all interventions without any difference of changes, a result which is consistent with previous studies (Kataura et al., 2017; Takeuchi and Nakamura, 2020b; Takeuchi et al., 2021a; 2021b). Change in ROM after a stretching intervention is attributed to changes in the stretching tolerance and muscle-tendon unit stiffness (Magnusson et al., 1996, 2001; Behm et al., 2016). The present study measured the passive torque at end ROM to assess any change in stretching tolerance, and the results indicated that the stretching tolerance increased in all interventions without any difference of change (Weppler and Magnusson, 2010; Takeuchi et al., 2021a, 2021c; 2021d).

Therefore, it was suggested that high-intensity static stretching produced a large increase in the knee extension ROM due to the large decrease in the muscle-tendon unit stiffness, even with a uniform prescribed load of stretching.

In the present study, there was a significant correlation between the static stretching load and relative change in the knee extension ROM, but there was no significant correlation between the static stretching load and relative change in the passive torque at end ROM, which is consistent with previous studies (Takeuchi et al., 2021b). Moreover, there was a significant correlation between the static stretching load and relative change in the muscle-tendon unit stiffness of all interventions. Takeuchi et al. (Takeuchi et al., 2021b) reported a significant relationship between the static stretching load and relative change in the ROM and muscle-tendon unit stiffness when analyzing the relationship of normal- and high-intensity static stretching together. These results indicated that the applied load of static stretching is an important factor for decreasing the muscle-tendon unit stiffness of the hamstrings when analyzing the static stretching load of low-, normal-, and high-intensity static stretching together. In the next paragraphs, we discuss the change in the muscle-tendon unit stiffness for each stretching intensity in detail.

The muscle-tendon unit stiffness did not change at 80%POD (total of 225 seconds of stretching), but it decreased at 100%POD (total of 180 seconds of stretching). Moreover, the results of the present study showed that there were significant negative correlations between the static stretching load and changes in the muscle-tendon unit stiffness at 80%POD and 100%POD respectively. Previous studies reported that the muscle-tendon unit stiffness of the hamstrings was not changed after 180 seconds of static stretching at the intensity of 80%POD (Kataura et al., 2017; Nakamura et al., 2021a), but it decreased after 600 seconds of low-intensity stretching (Freitas et al., 2015). In addition, in static stretching at the intensity of 100%POD, 180 seconds of stretching duration is needed to decrease the muscle-tendon unit stiffness of the hamstrings (Matsuo et al., 2013; Nakamura et al., 2019). It was suggested that the applied load of static stretching is an important factor for the decrease in the muscle-tendon unit stiffness of low- and moderate-intensity static stretching.

At 120%POD, the muscle-tendon unit stiffness decreased after 50 seconds of high-intensity static stretching, and thereafter the change in the stiffness plateaued. In addition, there was no significant correlation between the static stretching load and change in the muscle-tendon unit stiffness at 120%POD. Previous studies reported that static stretching at the intensity of 120%POD for 20 - 60 seconds significantly decreased the muscle-tendon unit stiffness of the hamstrings (Takeuchi and Nakamura, 2020a; Fukaya et al., 2021; Takeuchi et al., 2021a; 2021c). In addition, a previous study reported that the decrease in the muscle-tendon unit stiffness of static stretching at the intensity of approximately 130 - 140%POD reached a plateau within 10 seconds (Takeuchi and Nakamura, 2020b). The minimum duration required for a change in the muscle-tendon unit stiffness in static stretching at the intensity of 120%POD is unclear. However, it was indicated that the decrease in the muscle-tendon unit stiffness of 120%POD might reach a plateau in a shorter time than 50 seconds, and as a result, there may not be a significant correlation between the static stretching load and the relative change in the muscle-tendon unit stiffness. In the present study, the median value of the static stretching load of Set 1 at 120%POD was 698.3 Nm, which was lower than the total static stretching load of the three sets of 100%POD (median value of 1165.0 Nm), although one set of 120%POD was the most effective in decreasing the stiffness. Taken together, it was suggested that the applied load of static stretching could not be an important factor for the decrease in the muscle-tendon unit stiffness for high-intensity static stretching.

There were some limitations in this study. Firstly, there may be sex differences in the effects of static stretching at the intensity of 100%POD (Kato et al., 2005; Morse, 2011). Therefore, sex differences also need to be examined. Secondly, high-intensity static stretching is associated with low to moderate stretching pain (Takeuchi and Nakamura, 2020a; 2020c). The pain usually disappears immediately after a stretching intervention, but may affect the effectiveness of stretching. Finally, the present study examined the acute effects of static stretching load on the changes in the flexibility of the hamstrings. A review study indicated that static stretching for less than 8 weeks could not change the muscle-tendon stiffness (Freitas et al., 2018), but a recent study found static stretching for 24-weeks significantly decreased the stiffness (Moltubakk et al., 2021). Furthermore, the effect of long-term high-intensity static stretching on stiffness is controversial (Muanjai et al., 2017; Nakamura et al., 2021b; Fukaya et al., 2021). The long-term effects of the prescribed and applied loads of static stretching need to be further examined.

Conclusion

High-intensity static stretching was effective for a decrease in the muscle-tendon unit stiffness of the hamstrings even when the prescribed load of static stretching was unified. Moreover, the applied load of static stretching was an important factor in decreasing the muscle-tendon unit stiffness in low- and moderate-intensity static stretching, but not in high-intensity stretching.

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Key points

- The effects of the prescribed and applied load of static stretching on the muscle-tendon unit stiffness of the hamstrings were examined by using different intensities and durations of static stretching.
- High-intensity static stretching was the most effective for a decrease in the muscle-tendon unit stiffness even when the prescribed load was unified.
- The applied load was important for the stiffness in low- and normal-intensity static stretching, but not in high-intensity stretching.

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