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ORIGINAL ARTICLE

# Acute and chronic effects of static stretching at 100% versus 120% intensity on flexibility

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## Abstract
**Purpose** The acute effects of static stretching have been frequently studied, but the chronic effects have not been studied concurrently. Thus, this study aimed to investigate both the acute and chronic effects of static stretching at different intensities on flexibility.

**Methods** Twenty-three healthy men were randomly assigned to perform 1 min of static stretching 3 days/week for 4 weeks at 100% intensity ($n=12$) or 120% intensity ($n=11$). The acute effects of stretching were assessed by measuring the range of motion (ROM), peak passive torque, and passive stiffness before and after every stretching session; the chronic effects of stretching were assessed by measuring these outcomes at baseline and after 2 and 4 weeks of stretching.

**Results** Compared with the 100% intensity group, the 120% intensity group had significantly greater acute increases in ROM after all 12 sessions, a significantly greater decrease in passive stiffness after 11 of 12 sessions, and a significantly greater increase in peak passive torque after six of 12 sessions. Regarding the chronic effects, ROM was significantly increased in both groups after 2 and 4 weeks of stretching. Peak passive torque significantly increased in the 100% intensity group after 2 and 4 weeks of stretching, and after 4 weeks in the 120% intensity group.

**Conclusion** Stretching at 120% intensity resulted in significantly greater acute improvements in ROM, peak passive torque, and stiffness than stretching at 100% intensity. Four weeks of stretching increased ROM and peak passive torque but did not decrease passive stiffness, regardless of the stretching intensity.

**Keywords** Static stretching · Stretching intensity · Flexibility · Passive stiffness · Acute effects · Chronic effects

### Abbreviations

MTU Muscle–tendon unit
ROM Range of motion
SPT Static passive torque

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## Introduction

Stretching is commonly performed in sports and rehabilitation. Static stretching involves passively stretching the target muscle to a new length and holding this for some time (Magnusson et al. 1995). The main purpose of static stretching is to improve flexibility. Flexibility varies between individuals but has been defined as the ability to move a joint through its complete range of motion (ROM), which is important for sports performance and the ability to carry out activities of daily living (Pescatello et al. 2013). Static stretching increases ROM by increasing the subject's capacity to tolerate loading prior to stretch termination (i.e., increased stretch tolerance) and changing the viscoelastic properties of the muscle–tendon unit (MTU) (i.e., decreased passive stiffness) (Behm et al. 2016).

Many studies have attempted to determine the best static stretching method to improve flexibility, using ROM, stretch tolerance, and passive stiffness as the outcomes of flexibility. The four stretch parameters that have been described as being associated with an improvement in flexibility in response to static stretching are intensity, duration, position, and frequency (Apostolopoulos et al. 2015). However, few studies have investigated the effects of different stretching intensities on flexibility (Freitas et al. 2015a, 2016; Young et al. 2006; Kataura et al. 2017). Generally, the recommended stretching intensity is the maximal ROM without pain or discomfort (Anderson and Anderson 1980). However, Freitas et al. (2015b) suggested that a greater stretching intensity is more effective in acutely improving flexibility. Additionally, we recently reported that high-intensity static stretching with pain acutely increases flexibility compared with static stretching without pain (Kataura et al. 2017).

The effects of static stretching on flexibility are usually studied as acute and chronic effects. Mizuno et al. (2013b) reported that the increased ROM achieved after 5 min of stretching is returned to baseline within 1 h. Additionally, Hatano et al. (2017) reported that the increase in ROM continues for more than 30 min after stretching, but passive stiffness returns to baseline within 30 min. Therefore, it might be difficult to obtain a chronic or prolonged improvement in flexibility after performing only a single stretching session. To improve flexibility in a more chronic fashion, the American College of Sports Medicine recommends 10–60 s of stretching for a minimum of 3 days/week for 3 or 4 weeks (Pescatello et al. 2013). Many studies have used this protocol and reported chronic increases in ROM (Cipriani et al. 2012; Marques et al. 2009; Nakamura et al. 2017). However, few studies have investigated the chronic effects of different stretch parameters on flexibility, and the intensity of the stretching is inconsistently reported. One previous study found that chronic static stretching of varying durations and frequency significantly increased ROM, but no significant difference between each stretching condition (Bandy and Irion 1994). Similarly, another study showed that the increase in ROM due to chronic static stretching is independent of stretching intensity (Muanjai et al. 2017). Wyon et al. reported that low-intensity static stretching was more effective in improving ROM than moderate or high-intensity stretching (Wyon et al. 2009, 2013). However, it is possible that the chronic effects that the static stretch parameters evaluated in previous studies had on flexibility might not have significantly differed in accordance with stretching duration, frequency, and intensity because they did not simultaneously investigate how the acute effects of stretching change during the stretching program. Furthermore, as many previous studies only investigated the chronic effects of static stretching, it remains unclear how the acute effects of static stretching on flexibility are associated with the chronic effects.

The purpose of the present study was to investigate the acute and chronic effects of different static stretching intensities on flexibility. We hypothesized that the chronic effects on flexibility of stretching at 120% intensity are greater than the chronic effects of stretching at 100% intensity because the acute effects of stretching at 120% intensity are greater than the acute effects of stretching at 100% intensity.

## Methods

### Subjects

Twenty-four healthy men (age, 20.0 ± 1.5 years; height, 170.0 ± 6.1 cm; body weight, 62.5 ± 7.3 kg) voluntarily participated in the present study after providing written informed consent. The subjects had not performed flexibility training for at least 6 months prior to the study. The exclusion criteria were: history of surgery on the back or lower extremities, lower extremity contracture, neurological disorder, intake of hormones or muscle affecting drugs. None of the participants played competitive sports, performed regular flexibility training, or achieved a full extension of the knee (with the hip flexed at approximately 110 degrees) during the ROM assessment. This study was approved by the Human Research Ethics Committee of our institution (15-506, 15-24).

The sample size was calculated using G*Power software (v 3.0.10; Franz Faul, Kiel University, Kiel, Germany) on the basis of the findings of a previous study (Cipriani et al. 2012). The effect size was calculated when ROM was significantly increased after 4 weeks of static stretching training compared with baseline values measured before stretching. On the basis of the effect size, with $\alpha = 0.05$ and power = 0.80, the minimum required number of subjects was eight in each group.

### Study design and overview

Subjects were randomly assigned to the 100% intensity group or the 120% intensity group. ROM, peak passive torque, and passive stiffness at baseline were not significantly different between the 100% and 120% groups. The hamstring muscles were targeted for the stretching exercises. Randomization was performed using the permuted block method with a set block size of four. The 100% and 120% intensity groups performed 60 s of stretching at 100% or 120% intensity, respectively, 3 days per week for 4 weeks. To examine the acute effects of stretching, ROM, peak passive torque (as a measure of stretch tolerance) (Halbertsma and Goeken 1994), and passive stiffness were measured before and after every stretching session. To examine the chronic effects of stretching, these outcomes were measured before and after 2 and 4 weeks of stretching. These outcomes were measured 1–4 days after the final stretching session (Blazevich et al. 1985; Ben and Harvey 2010).

## Procedures

### Measurements of range of motion, peak passive torque, and passive stiffness

ROM, peak passive torque, and passive stiffness were calculated from the torque–angle relationship measured using an isokinetic dynamometer. Measurements were taken with the subject in a sitting position with approximately 110° hip and knee joint flexion, as done in previous studies (Matsuo et al. 2013; Kataura et al. 2017) (Fig. 1a). Prior to the stretching exercises and testing we did not perform any warm-up exercises because Fujita and colleagues reported that pedaling exercises or a hot pack prior to static stretching did not additionally decrease muscle–tendon stiffness compared with performing stretching alone (Fujita et al. 2018). The participants were seated on the chair of the isokinetic dynamometer (Primus RS; BTE Technologies, Hanover, MD, USA) with the seat maximally tilted and a wedge-shaped cushion inserted between the trunk and the backrest to create an angle of approximately 60° between the seat and the back. The chest, pelvis, and right thigh were stabilized with Velcro straps. The knee joint was aligned with the axis of rotation of the isokinetic dynamometer, and the lever arm attachment was placed proximal to the malleolus medialis and stabilized with Velcro straps. While each participant was sitting in the chair, the knee was extended passively at a rate of 5°/second to the point of maximum knee extension just before the onset of pain, and the torque was recorded continuously to obtain the torque–angle relationship during passive knee extension. The torque and angle signals were A/D converted and stored in a personal computer (Dynabook KIRA V63, Toshiba, Tokyo, Japan) for analyses.

ROM was defined as the maximum knee extension angle from the initial position (0°), while peak passive torque (Nm) was defined as the point of maximal knee extension without pain (Halbertsma and Goeken 1994; Magnusson et al. 1995; Matsuo et al. 2013). Passive stiffness (Nm/°) was defined as the slope of the regression line that was calculated from the torque–angle curve using the least square method (Matsuo et al. 2013). Passive stiffness was calculated from the torque corresponding to 50% of the maximum knee extension angle of each participant when the minimum ROM was recorded, and the same angles were used for all time points (Matsuo et al. 2015).

### Measurement of passive torque during stretching

Passive torque produced by the hamstrings during static stretching was measured at stretching angle at 200 Hz. An isokinetic dynamometer was used, and the torque signal was

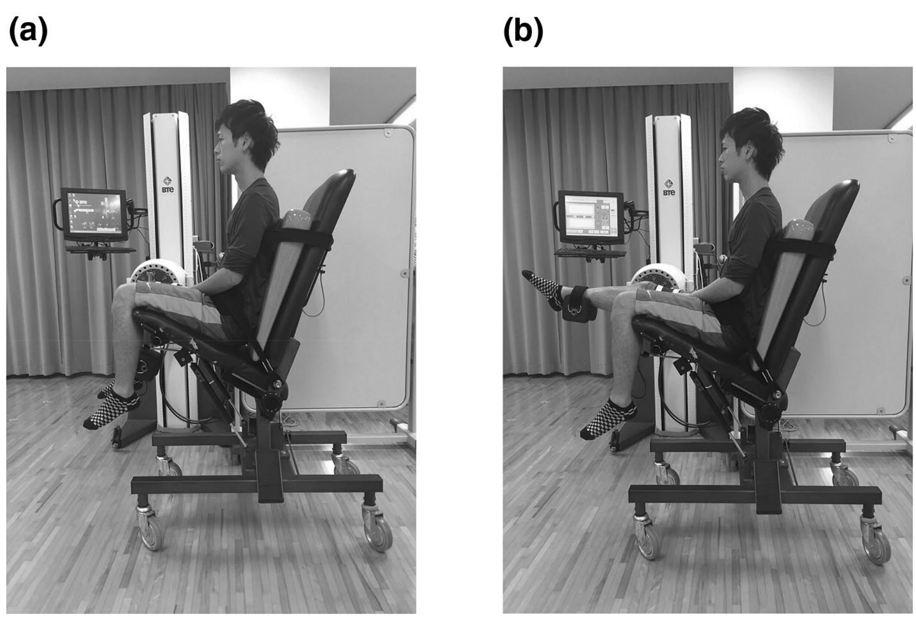


**Fig. 1** Photograph showing the position assumed by the subjects for static stretching of the knee flexors. **a** Before stretching. **b** During stretching

transferred to an A/D converter (PowerLab; ADInstruments, NSW, Australia) and stored in a personal computer for later analyses. Based on previous studies (Matsuo et al. 2013), the change in static passive torque (SPT) from the onset to the end of each stretching session was calculated using LabChart 8 software (ADInstruments) and compared.

### Static stretching program

The participants performed 60 s of static stretching at 100% or 120% intensity of the right knee flexor muscle in the sitting position using the isokinetic dynamometer (Fig. 1b). A stretching intensity of 100% was defined as the maximum tolerable ROM without pain (Kataura et al. 2017; Matsuo et al. 2013), and the stretching angle at 100% or 120% intensity was decided by the ROM, which was measured before each stretching session. Stretching was conducted 3 days per week for 4 weeks, so the total time spent stretching for each participant was 720 s.

### Statistical analysis

The test–retest reliabilities for ROM, peak passive torque, and passive stiffness were determined before the present study using two tests performed in five healthy men on different days. The calculated intraclass correlation coefficients for ROM, peak passive torque, and passive stiffness were 0.80 (95% CI, 0.09–0.98), 0.87 (95% CI, 0.31–0.98), and 0.97 (95% CI, 0.57–0.99), respectively, indicating that the reliability was high for all outcome measures (Landis and Koch 1977). The coefficients of variation calculated for the outcome measures also showed acceptable levels of reliability (2.8% for ROM, 5.0% for peak passive torque, and 6.6% for passive stiffness) (Portney 1993).

The normality of the data was assessed with the Shapiro–Wilk test. This test showed that some of the dependent variables were not normally distributed. Therefore, nonparametric tests were applied to all variables. To evaluate the acute effects of stretching, the Wilcoxon's signed-rank test was performed to compare the pre- and post-stretching values of the outcome measures for each of the 12 stretching sessions. To compare the acute effects of stretching at 100% versus 120% intensity, the Mann–Whitney *U*-test was applied to assess the relative changes in ROM, peak passive torque, and passive stiffness values from before to after stretching for each of the 12 sessions. To evaluate the chronic effects of stretching, the Freidman test was applied to compare the differences in the outcome measures between timepoints. When a significant difference was found, a Bonferroni post-hoc test was performed to locate a significant difference from the baseline value. The Mann–Whitney *U*-test was applied to the dependent variable to compare the differences between stretching at 100% or 120% intensity for each time point. In addition, Spearman's rank-order correlation analysis was conducted to assess the changes in SPT, ROM, peak passive torque, and passive stiffness. All statistical analyses were performed using SPSS (IBM SPSS statistics, version 24.0, IBM Corp., Armonk, NY, USA), and significance was set at $p < 0.05$. All data are presented as mean ± standard deviation.

## Results

One subject in the 120% intensity group was withdrawn because he missed all 12 stretching sessions; the other 23 subjects completed all sessions. The characteristics of the subjects in both groups are summarized in Table 1. For only the first stretching session, the data for one of the 11 subjects in the 120% intensity group were excluded because the angle data were incorrect.

### Acute effects of stretching at 100% or 120% intensity

ROM significantly increased from pre- to post-stretching for each of the 12 stretching sessions in both the 100% and 120% intensity groups (Fig. 2a, b). The relative change in ROM was significantly greater in the 120% intensity group than the 100% intensity group for all 12 stretching sessions (Fig. 2c). Similarly, peak passive torque significantly increased from pre- to post-stretching in both groups for all 12 stretching sessions (Fig. 3a, b). The increase in peak passive torque was significantly greater in the 120% intensity group than the 100% intensity group for six of the 12 stretching sessions (50.0% of the sessions) (Fig. 3c). Passive stiffness significantly decreased from pre- to post-stretching in the 120% intensity group for all 12 stretching sessions, but only for six of the 12 sessions in the 100% intensity group (50% of the sessions) (Fig. 4a, b). The decrease in passive stiffness was significantly greater in the 120% intensity group than the 100% intensity group for 11 of the 12 stretching sessions (91.7% of the sessions) (Fig. 4c).

**Table 1** Physical characteristics of the subjects

| Characteristics | 100% stretching groups | 120% stretching groups |
|---|---|---|
| Participants | $N = 12$ | $N = 11$ |
| Age (years) | 20.0 ± 1.8 | 20.1 ± 1.2 |
| Height (cm) | 170.9 ± 7.1 | 169.0 ± 5.4 |
| Body mass (kg) | 61.5 ± 6.6 | 63.6 ± 8.4 |
| Body Mass Index (kg/m$^2$) | 21.1 ± 2.2 | 22.2 ± 2.2 |

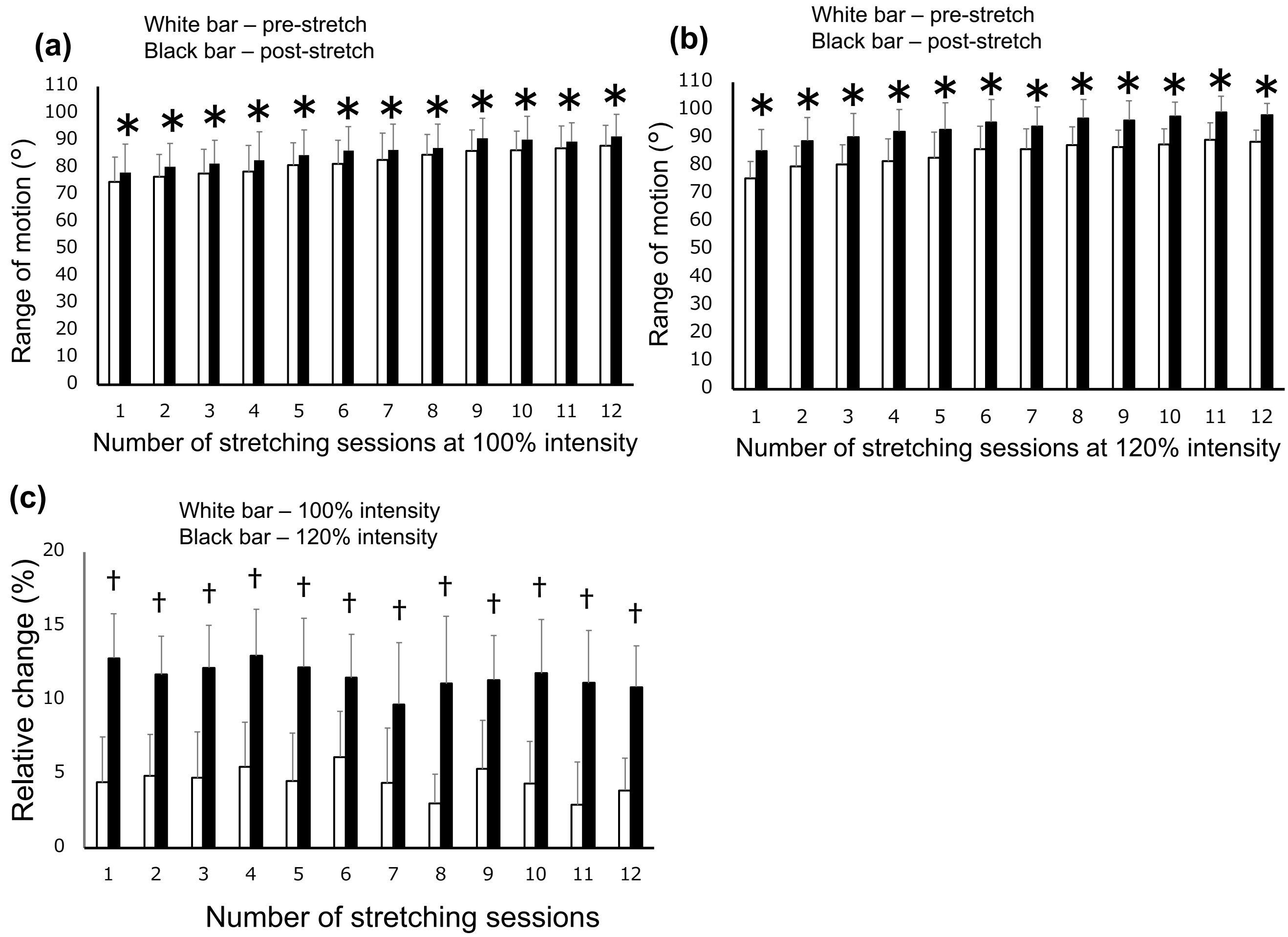


**Fig. 2** Acute effects of static stretching on range of motion. Pre-stretching values (white columns) and post-stretching values (black columns) for subjects stretching at **a** 100% intensity and **b** 120% intensity for all 12 stretching sessions. **c** Relative change in ROM after stretching at 100% intensity (white columns) and 120% intensity (black columns). Data are presented as mean and standard deviation. $*p<0.05$ vs. pre-stretching. $\dagger p<0.05$ vs. stretching at 100% intensity

The SPT significantly decreased from pre- to post-stretching in the 100% and 120% intensity groups for all 12 stretching sessions (Fig. 5a, b). The relative change in SPT was significantly greater in the 120% intensity group than the 100% intensity group for nine of the 12 stretching sessions (75.0% of the sessions) (Fig. 5c). Moreover, there was a moderate correlation between the relative changes in SPT and ROM ($\rho = -0.438$, $p < 0.05$), and between the relative changes in SPT and passive stiffness ($\rho = 0.403$, $p < 0.05$). There was a slight negative correlation between the relative changes in SPT and peak passive torque ($\rho = -0.150$, $p < 0.05$).

### Chronic effects of stretching at 100% or 120% intensity

ROM was significantly increased in both the 100% and 120% groups after 2 and 4 weeks of stretching. Peak passive torque significantly increased in the 100% intensity group after 2 and 4 weeks of stretching, but significantly increased only after 4 weeks of stretching in the 120% intensity group. (Table 2). However, the relative changes in ROM and peak passive torque did not significantly differ between groups. Passive stiffness did not significantly decrease from baseline to 2 and 4 weeks after stretching in either the 100% or 120% intensity groups.

## Discussion

The present study investigated the acute and chronic effects of static stretching at two different intensities (100% and 120%) on ROM, peak passive torque, and passive stiffness. The acute effects of stretching at 120% intensity resulted in greater improvements in ROM, peak passive torque, and stiffness than stretching at 100% intensity. However, the chronic effects of stretching did not differ in accordance

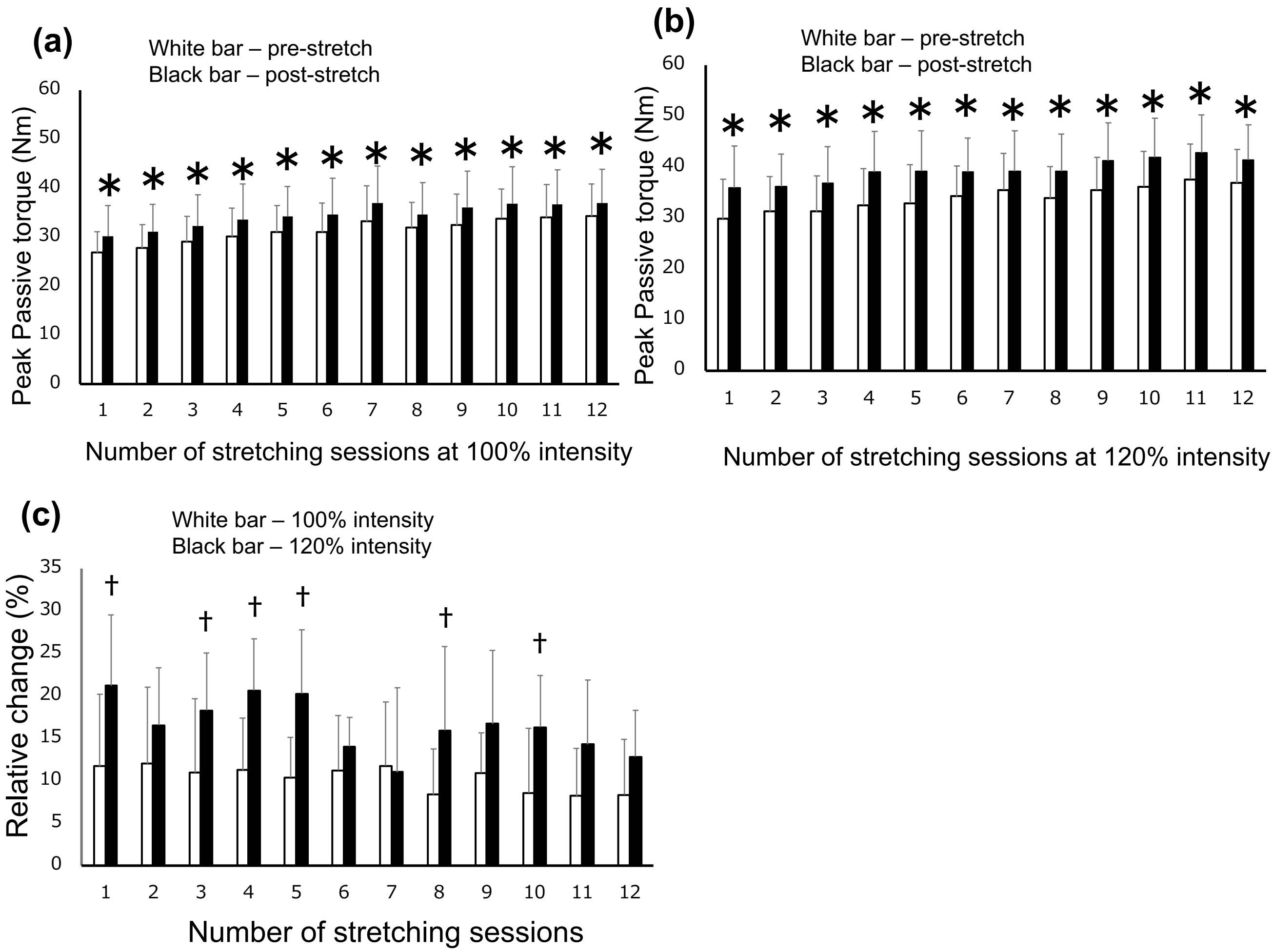


**Fig. 3** Acute effects of static stretching on peak passive torque. Pre-stretching values (white columns) and post-stretching values (black columns) for subjects stretching at **a** 100% intensity and **b** 120% intensity for all 12 stretching sessions. **c** Relative change in peak passive torque after stretching at 100% intensity (white columns) and 120% intensity (black columns). Data are presented as mean and standard deviation. *$p < 0.05$ vs. stretching at 100% intensity. †$p < 0.05$ vs. stretching at 100% intensity

with stretching intensity. The present results suggest that the stretching intensity causes no difference in the chronic effects on flexibility, but stretching at 120% intensity has greater acute effects on flexibility than stretching at 100% intensity.

## Acute effects of stretching at 100% and 120% intensity on flexibility

In the present study, static stretching at 100% intensity resulted in a significant increase in ROM and peak passive torque after all stretching sessions, and a decrease in passive stiffness after 50.0% of sessions (six of 12 stretching sessions). In contrast, the 120% intensity group showed a decreased passive stiffness and increased peak passive torque after all 12 stretching sessions. The mechanism of the increase in ROM is the increase in the capacity to tolerate loading prior to stretch termination (the increase in stretch tolerance) and the improvement in viscoelastic properties (for example, the reduction in passive stiffness) (Mizuno et al. 2013b; Behm et al. 2016). Therefore, the present results suggest that the immediate increase in ROM in the 100% intensity group was mainly associated with a change in stretch tolerance, but not with a change in the passive stiffness. In contrast, the increase in ROM in the 120% intensity group was associated with a change in stretch tolerance and the change in the passive stiffness. Surprisingly, passive stiffness was decreased after all stretching sessions in the 120% intensity group. In contrast, a previous study reported that passive stiffness is not changed after 60 s of stretching at 100% intensity, and more than 180 s of stretching is required to decrease stiffness (Matsuo et al. 2013). To our knowledge, no study has reported a decrease in the passive stiffness of the hamstrings after 60 s of stretching. Kataura

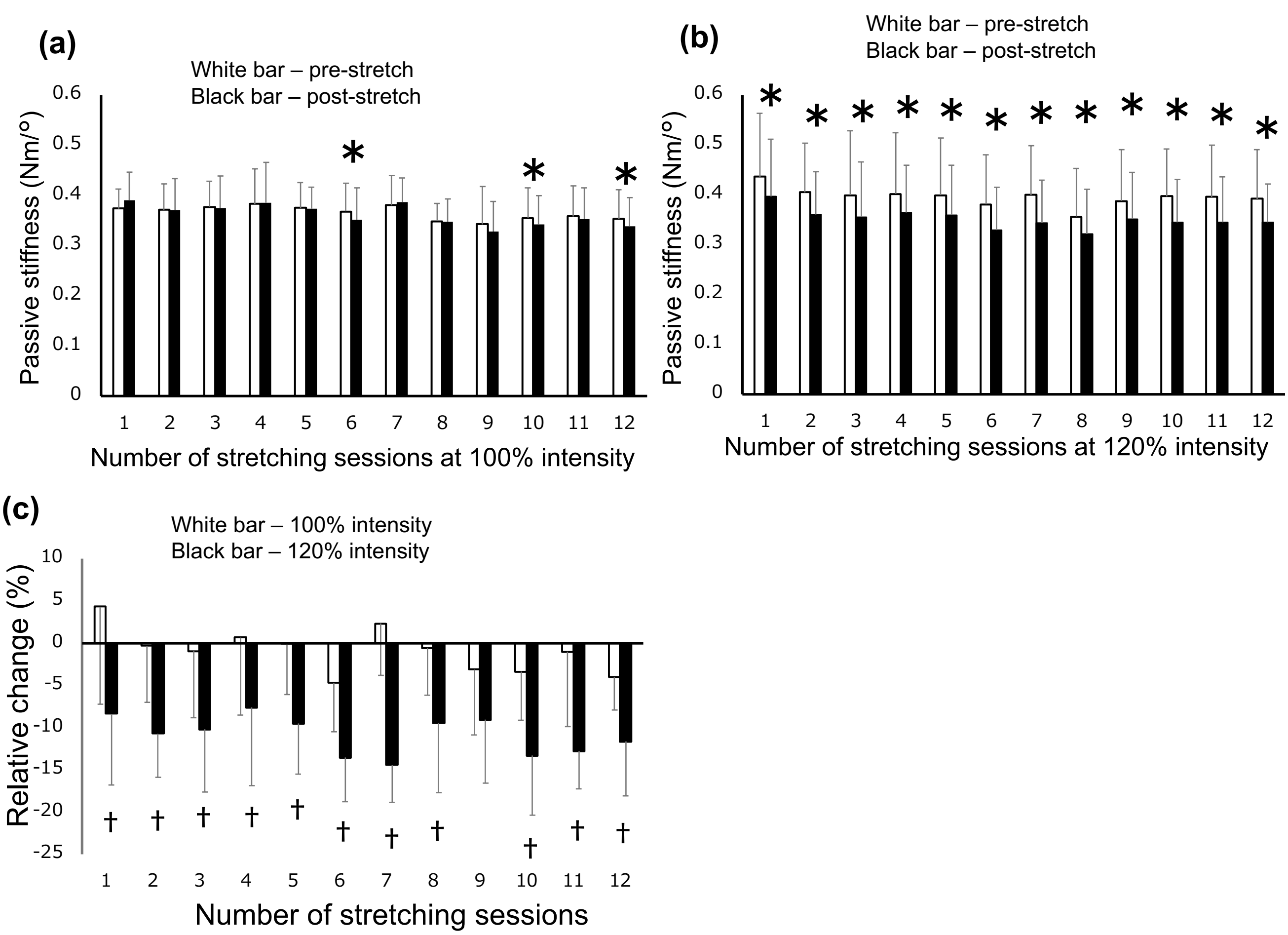


**Fig. 4** Acute effects of static stretching on passive stiffness. Pre-stretching values (white columns) and post-stretching values (black columns) for subjects stretching at **a** 100% intensity and **b** 120% intensity for all 12 stretching sessions. **c** Relative change in passive stiffness after stretching at 100% intensity (white columns) and 120% intensity (black columns). Data are presented as mean and standard deviation. *$p < 0.05$ vs. pre-stretching. †$p < 0.05$ vs. stretching at 100% intensity

et al. (2017) reported that stretching at greater intensity is more effective for increasing ROM and decreasing passive stiffness than stretching at a lesser intensity. Therefore, the high-intensity stretching performed in the present study may have shortened the stretching duration required to decrease passive stiffness.

The present study showed that the post-stretching increase in ROM was greater in the 120% intensity group than in the 100% intensity group. Similarly, the change in passive stiffness was significantly greater in the 120% intensity group than in the 100% intensity group after 91.7% of the 12 stretching sessions. In contrast, the 120% intensity group showed a greater improvement in peak passive torque than the 100% intensity group after only 50.0% of the 12 stretching sessions. Kataura et al. (2017) reported that stretching at greater intensity does not effectively increase stretch tolerance. Therefore, the greater increase in ROM in the 120% intensity group than the 100% intensity group may have occurred because of a decrease in passive stiffness rather than an increase in stretch tolerance. To our knowledge, the mechanism of increasing stretch tolerance remains unclear. Previous studies have proposed that the increase in stretch tolerance is caused by a reduction in the perceptions of pain and discomfort accompanied by a change in neural and psychological factors after stretching (Folpp et al. 2006; Law et al. 2009). The relationship between the change in stretch tolerance and the stretching intensity should be investigated in a future study.

The present study found a moderate correlation between the degree of SPT decrease and the relative changes in ROM and passive stiffness, while there was only a slight correlation between the relative changes in SPT and peak passive torque. However, to our knowledge, no study has investigated the association between stress relaxation during stretching and passive stiffness. The decrease in SPT during stretching is caused by stress relaxation, which is the decline in passive torque when a muscle is stretched and held at a constant length (Magnusson et al. 1995; Taylor

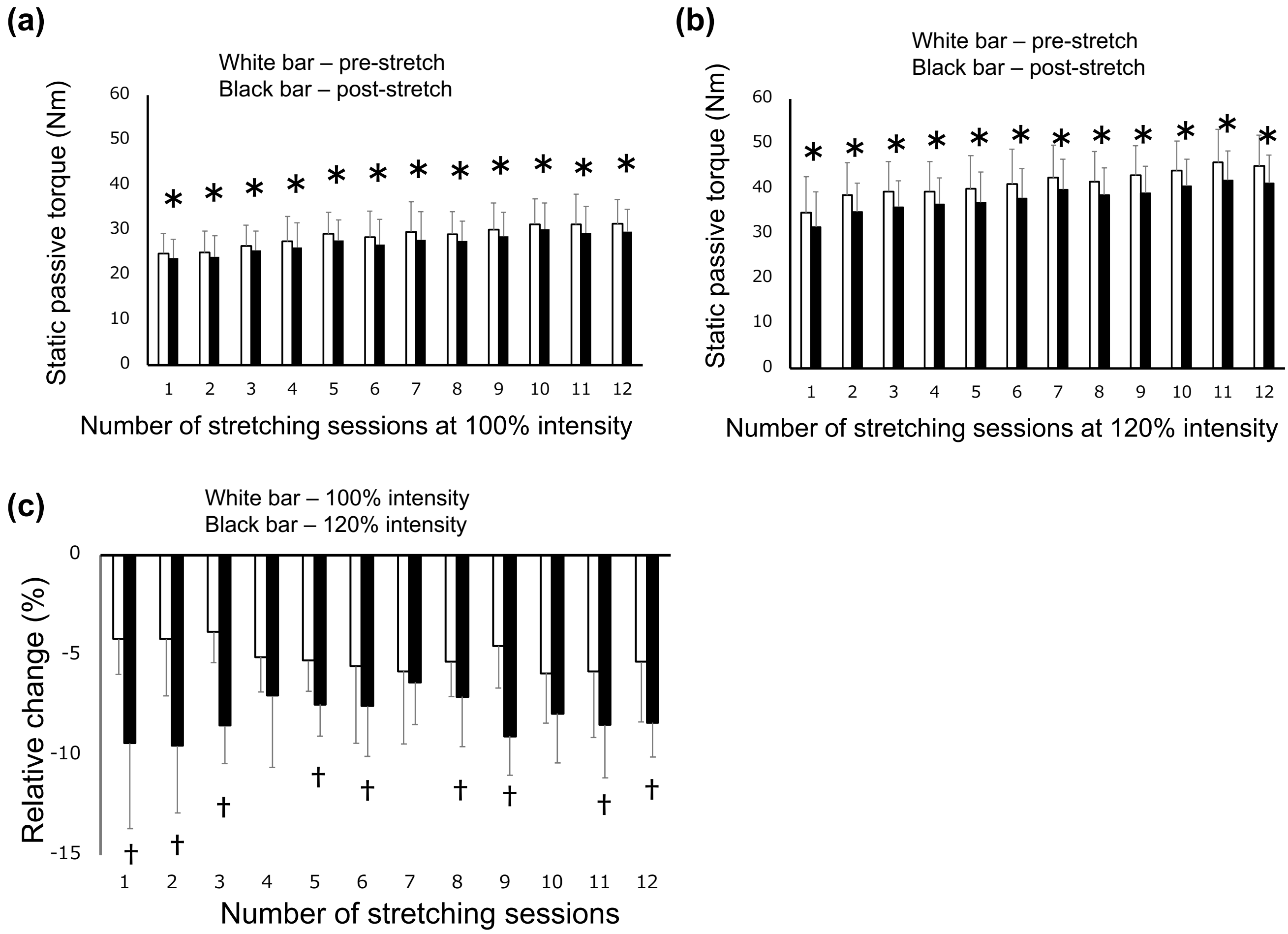


**Fig. 5** Acute effects of static stretching on static passive torque. Pre-stretching values (white columns) and post-stretching values (black columns) for subjects stretching at **a** 100% intensity and **b** 120% intensity for all 12 stretching sessions. **c** Relative change in static passive torque after stretching at 100% intensity (white columns) and 120% intensity (black columns). Data are presented as mean and standard deviation. $*p<0.05$ vs. pre-stretching. $\dagger p<0.05$ vs. stretching at 100% intensity

**Table 2** Chronic effects of static stretching at 120% or 100% intensity on ROM, peak passive torque, and passive stiffness

| | ROM (°) relative change (%) | | Peak passive torque (Nm) relative change (%) | | Passive stiffness (Nm/°) relative change (%) | |
|---|---|---|---|---|---|---|
| | 100% groups | 120% groups | 100% groups | 120% groups | 100% groups | 120% groups |
| Baseline | 74.9 ± 7.6 | 77.2 ± 5.7 | 28.0 ± 4.8 | 29.8 ± 9.6 | 0.40 ± 0.05 | 0.42 ± 0.14 |
| 2 weeks | 82.7 ± 9.6* (10.3 ± 6.3) | 86.0 ± 7.0* (11.4 ± 7.0) | 32.0 ± 6.1* (14.6 ± 9.5) | 34.1 ± 6.8 (17.9 ± 16.7) | 0.37 ± 0.05 (− 6.2 ± 16.0) | 0.37 ± 0.1 (− 7.9 ± 14.2) |
| 4 weeks | 88.7 ± 6.9* (18.8 ± 7.2) | 90.0 ± 4.6* (16.7 ± 5.5) | 36.2 ± 6.9* (30.1 ± 17.1) | 38.2 ± 6.7* (33.3 ± 23.3) | 0.36 ± 0.05 (− 7.9 ± 12.6) | 0.39 ± 0.08 (− 2.8 ± 17.2) |

Data are presented as mean ± standard deviation

*ROM* range of motion

$^{*}p<0.05$ compared with baseline

et al. 1990). In the present study, the relative change in SPT was greater in the 120% intensity group than in the 100% intensity group. Similarly, Freitas et al. (2015a) suggested that the absolute effect on the SPT is dependent upon the stretching intensity. In addition, the greatest amount of stress relaxation in tissue is reportedly seen at the greatest extensions in vivo (Purslow et al. 1998), and stress relaxation is correlated with the change in the muscle–tendon junction displacement (Nakamura et al. 2013) or the change in fascicle length (Kato et al., 1985). Therefore, the present results suggest that greater stress relaxation was caused by greater extension of the MTU, which resulted in a greater change in passive stiffness than in stretch tolerance.

### Chronic effects of stretching at 100% and 120% intensity on flexibility

The present study found that ROM significantly increased from baseline to 2 and 4 weeks after stretching at intensities of 100% and 120%. The relative change in ROM after 4 weeks of stretching at 100% intensity in the present study was 18.8%, which is similar to the results of a previous study that used the same protocol (Cipriani et al. 2012). However, contrary to our hypothesis, there was no difference in the relative change in ROM after stretching at 100% versus 120% intensity, although stretching at 120% intensity had a greater acute effect on ROM than stretching at 100% intensity. Therefore, the differences in the acute effects of static stretching at different intensities on ROM did not influence the chronic effects. As mentioned above, the mechanism of the acute effects of stretching on ROM is to increase peak passive torque and decrease passive stiffness (Matsuo et al. 2013; Behm et al. 2016). The present study showed that 4 weeks of stretching at intensities of 100% and 120% resulted in a significant increase in peak passive torque, but no significant decrease in passive stiffness. Therefore, the present results suggest that the chronic effect of stretching on ROM was associated with an increase in stretch tolerance, but not with a long-term change in the viscoelastic properties of the MTU in both groups. This result is similar to previous studies that reported that the chronic effects of stretching on ROM are mainly caused by an increase in stretch tolerance (Halbertsma and Goeken 1994; Gajdosik et al. 2007; Folpp et al. 2006). Moreover, the present results showed that the chronic effect of stretching on peak passive torque did not differ between groups. Similarly, Muanjai et al. (2017) reported no significant difference in the increase in maximum passive torque after 4 weeks of stretching at different intensities, using the point of pain and discomfort as indicators of stretching intensity. Thus, the reason that the chronic effect of stretching on ROM did not differ in accordance with stretching intensity in the present study may be because stretching at 100% and 120% intensity resulted in similar increases in stretch tolerance.

Contrary to the results for the changes in ROM and peak passive torque, both groups showed no change in passive stiffness after 4 weeks of stretching, even though acute effects of stretching on passive stiffness were observed. Freitas et al. (2018) suggested that structural MTU adaptations as a consequence of stretching may need a longer intervention duration of at least 8 weeks. In the present study, the subjects performed stretching for 4 weeks, which might not have been sufficient to change the passive stiffness. Moreover, Mizuno et al. (2013a) and Hatano et al. (2017) reported that the decline in passive stiffness returns to baseline within 30 min after stretching. Thus, it is possible that the acute decline in passive stiffness seen in the present study after stretching at 100% and 120% intensity was not maintained until the next stretching session, and so the chronic effect of stretching on passive stiffness showed no change after 4 weeks. Overall, when comparing the acute effects of stretching at 100% and 120% intensity, the decrease in passive stiffness was significantly greater in the 120% group than in the 100% group after 91.7% of the 12 sessions. In contrast, the 120% intensity grouped showed a greater improvement in peak passive torque (stretch tolerance) than the 100% group after only 50% of the 12 stretching sessions. We suggest that the greater increase in ROM in the 120% intensity group than the 100% group may have occurred because of a decrease in passive stiffness rather than an increase in stretch tolerance. It is possible that the acute decline in passive stiffness seen in the present study after stretching at 100% and 120% intensity was not maintained until the next stretching session, leading to no chronic effect of stretching on passive stiffness (at 4 weeks). Thus, we believe that the findings of acute, but not chronic, differences between the different stretching intensities on flexibility, especially passive stiffness, were because the changes were not maintained until subsequent stretching sessions. Future studies are required to investigate whether the method of stretching causes a difference in the decline in passive stiffness that is maintained for 1 day.

### Limitations

The present study has some limitations. First, the intensity of stretching may have differed between subjects, as 100% intensity was defined as the maximum tolerable ROM without pain. Freitas et al. (2015c) investigated ROM and stretch tolerance with a verbal scale and a visual analog scale to assess the stretching intensity; these scales should be applied to define the intensity of stretching based on the ROM. Second, the present findings may not be applicable to all people. The present study included only healthy men, and so the results may not be generalizable to women, older adults, and unhealthy subjects. Third, the present study only investigated the effect of stretching on flexibility, not on performance or strength, and we were also unable to evaluate the mechanical properties of the structures of the muscle–tendon units. Future studies are necessary to verify the effects of stretching when targeting different subjects and evaluations. Finally, our results indicated that a greater degree of stress relaxation during stretching seemed to affect passive stiffness, but the relationships between SPT and ROM, peak passive torque, and passive stiffness require further investigation in a larger study population that includes women and older adults.

## Conclusions

The present study investigated the acute and chronic effects of two different intensities of static stretching on ROM, peak passive torque, and passive stiffness, and found that the intensity of stretching impacts the acute effects of stretching. Stretching at 120% intensity resulted in significantly greater acute improvements in ROM, peak passive torque, and stiffness than stretching at 100% intensity. However, the chronic effects of stretching did not differ in accordance with stretching intensity. ROM and peak passive torque were significantly increased after stretching at both intensities. Thus, the chronic increase in ROM was associated with an increase in stretch tolerance, but not with a long-term change in the viscoelastic properties of the MTU, regardless of the acute effects of stretching. Consequently, the stretching intensity does not affect the improvement of the chronic effects of stretching on flexibility, while stretching at 120% intensity has a greater impact on the acute effects of stretching than stretching at 100% intensity.

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**Author contributions** Conceptualization: TF, SM, MI, EY, WT, SS; Data curation: TF; Formal analysis: TF; Investigation: TF, SM; Methodology: TF, SM, MI, EY, WT, SS; Project administration: SM and MI; Supervision: YA and SS; Visualization: TF; Writing—original draft: TF; Writing—review and editing: SM, MI, WT, YA, SS; All authors approved the final version of the manuscript.

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**Availability of data and material** Data for this study are available upon reasonable request.

### Compliance with ethical standards

**Conflict of interest** All of the authors declare that there is no conflict of interest regarding this article.

**Ethics approval** All procedures performed involving human participants were in accordance with the ethical standards of the institutional committee and with the Helsinki declaration and its later amendments or comparable standards.

**Informed consent** Informed consent was obtained from all participants included in the study.

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