



## Effects of ankle position during static stretching for the hamstrings on the decrease in passive stiffness



Sayaka Nakao<sup>a,\*</sup>, Tome Ikezoe<sup>a</sup>, Masatoshi Nakamura<sup>b</sup>, Junya Saeki<sup>c,d</sup>, Takehiro Kato<sup>a</sup>, Jun Umehara<sup>a,d</sup>, Noriaki Ichihashi<sup>a</sup>

<sup>a</sup> Human Health Sciences, Graduate School of Medicine, Kyoto University, Japan

<sup>b</sup> Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Japan

<sup>c</sup> Faculty of Sport Sciences, Waseda University, Japan

<sup>d</sup> Research Fellow of the Japan Society for the Promotion of Science, Japan

### ARTICLE INFO

#### Article history:

Accepted 18 September 2019

#### Keywords:

Stretching

Flexibility

Range of motion

Stiffness

Straight leg raise

### ABSTRACT

Static stretching is frequently performed to improve flexibility of the hamstrings, although the ankle position during hamstring stretching has not been fully investigated. We investigated the effects of ankle position during hamstring stretching on the decrease in passive stiffness. Fourteen healthy men performed static stretching for the hamstrings with the ankle dorsiflexed and plantar-flexed in a randomized order on different days. The hip was passively flexed to the maximum angle which could be tolerated without stretch pain with the knee fully extended; this was maintained for 5 min, with 1-min stretching performed in 5 sessions. Final angles and passive stiffness were measured before and after stretching. The final angle was defined as that formed by the tibia and horizontal plane when the knee was passively extended from hip and knee angles at 90° flexion to the maximum extension angle which could be tolerated without stretch pain. Passive stiffness was determined by the slope of torque-angle curve during the measurement of the final angle. The final angle significantly increased after stretching with the ankle dorsiflexed and plantar-flexed, whereas passive stiffness significantly decreased only after stretching with the ankle plantar-flexed. The results suggest that passive stiffness decreases after stretching with the ankle plantar-flexed but not after stretching with the ankle dorsiflexed, although the range of joint motion increases regardless of the ankle position during 5-min stretching for the hamstrings. These results indicate that static stretching should be performed with the ankle plantar-flexed when aiming to decrease passive stiffness of the hamstrings.

© 2019 Elsevier Ltd. All rights reserved.

### 1. Introduction

Hamstring strain injury is one of the most common injuries in sports, accounting for over 12% of all sport injuries (Feeley et al., 2008; Orchard et al., 2013). Preventing strain injuries is important because injured players could not be involved in matches and training for a long time (Brooks et al., 2006), resulting in a reduction in their performance (Verrall et al., 2006). Previous studies have indicated that lower hip flexion or knee extension range of motion (RoM) measured prior to the season was related to hamstring strain injury during the season in elite male soccer players (Bradley and Portas, 2007; Witvrow et al., 2003). Therefore, it is assumed that a reduction in muscle flexibility is one of the risk

factors for strain injuries. As for improvement in muscle flexibility, many previous studies have reported the acute and long-term effects of static stretching (SS) intervention for the hamstrings on increasing RoM and decreasing passive stiffness of the hamstring musculotendinous unit (Ben and Harvey, 2010; Fasen et al., 2009; Laudner et al., 2016; Marshall et al., 2011; Matsuo et al., 2013; Nakao et al., 2019; Umegaki et al., 2015); therefore, SS is often used to prevent hamstring strain injury.

The following are some types of SS for the hamstrings: passive hip flexion with the knee angle at full extension (straight leg raising [SLR]), passive knee extension with the hip angle at 90° flexion in a supine position, and active trunk flexion with the knee angle at full extension and the foot on bed or plinth in a standing position (Decoster et al., 2005; Halbertsma et al., 1996; Ylinen et al., 2009). The ankle position during SS for the hamstrings is not consistent in clinical practice and literature; the ankles could be in the neutral position (Castellote-Caballero et al., 2014), plantar-flexed position

\* Corresponding author at: Human Health Sciences, Graduate School of Medicine, Kyoto University, 53 Kawahara-cho, Shogoin, Sakyo-ku, Kyoto 606-8507, Japan.

E-mail address: [nakao.sayaka.37s@kyoto-u.jp](mailto:nakao.sayaka.37s@kyoto-u.jp) (S. Nakao).

(O'Sullivan et al., 2009; Sullivan et al., 1992), or position in which “the toes are directed toward the ceiling” (i.e., between the neutral and dorsiflexed positions) (Bandy and Irion, 1994; Bandy et al., 1997; Bandy et al., 1998). In addition, many studies have not indicated the information of the ankle position. Thus, the ankle position during SS for the hamstrings has not been fully investigated.

Passive SLR is often used as an SS method for the hamstrings, and ankle position during SS using passive SLR could affect the effects of SS. With respect to the relationship between the hip and ankle joints, Andrade et al. (2016a) reported that the maximum ankle dorsiflexion angle significantly decreased when the hip was flexed to a greater extent compared to that when the hip was less flexed. The authors considered that this ankle angle restriction may be caused by a neural mechanism, such as an increase in mechanosensitivity of the peripheral nerves. In addition, it has been reported that the hip flexion angle during passive SLR with the ankle dorsiflexed was restricted compared to that with the ankle plantar-flexed (Gajdosik et al., 1985; Palmer et al., 2015), since sciatic nerve tension may increase when the ankle was in dorsiflexion (Andrade et al., 2016b). The effect of SS on the decrease in passive stiffness depends on SS intensity (i.e., joint angle during SS) (Freitas et al., 2015). Thus, it is assumed that SS with the ankle dorsiflexed has less effect on the decrease in passive stiffness than SS with the ankle plantar-flexed.

Laudner et al. (2016) investigated the effect of the ankle position during SS using passive SLR for the hamstrings and showed no difference in improvement in hip flexion RoM between SS with the ankle dorsiflexed and SS with the ankle plantar-flexed. However, since RoM may be affected by various factors including pain or sensory perception (McHugh et al., 1998), it has been pointed out that measuring only RoM may be insufficient to assess changes in mechanical factors such as the stiffness of the musculotendinous unit, ligament, and joint capsule, or structural changes in muscle length. Therefore, to assess changes in mechanical factors separately, passive stiffness, which is determined as the slope of the torque–angle curve during passive joint movement, has been recommended for the assessment of musculotendinous unit stiffness (Magnusson et al., 1996). Although previous studies reported that passive stiffness decreased after SS for the hamstrings (Magnusson et al., 1996; Nakao et al., 2019), no study has investigated whether the ankle position during SS for the hamstrings affects the decrease in passive stiffness.

This study aimed to investigate whether ankle position during SS of the hamstrings affects acute changes in passive stiffness and RoM. It was hypothesized that SS with the ankle plantar-flexed could lead to a greater reduction in passive stiffness than SS with the ankle dorsiflexed, and that the effects on RoM would be similar regardless of the ankle position during SS.

## 2. Methods

### 2.1. Design

A randomized, crossover design was used to investigate whether the ankle position during SS for the hamstrings affects the decrease in passive stiffness. The flowchart of the study is shown in Fig. 1. The participants visited a laboratory to perform SS for the hamstrings on two occasions at an interval of more than 48 h to avoid the effect of the first trial. Fourteen participants were randomly allocated to group A or B. The participants in group A performed SS with the ankle dorsiflexed in the first session and subsequently SS with the ankle plantar-flexed in the second session, whereas the participants in group B performed SS with the ankle plantar-flexed in the first session and SS with the ankle dorsiflexed in the second session. The following outcomes were

measured before and after SS in each session: maximum knee extension angle which the participant could tolerate without a stretch pain (final angle), passive torque at the final angle, and slope of passive torque–angle curve (passive stiffness). The final angle, passive torque at the final angle, and passive stiffness were measured as indicators of RoM, stretch tolerance, and musculotendinous unit stiffness of the hamstrings, respectively.

### 2.2. Participants

A total of 14 healthy young men (age,  $25.4 \pm 4.3$  years; height,  $170.9 \pm 5.2$  cm; mass,  $64.8 \pm 8.2$  kg) voluntarily participated in this study. Inclusion criteria were Japanese non-athletes who were not involved in regular stretching or training programs and who had no history of injuries or neuromuscular diseases in the lower leg or lumbar spine. Exclusion criteria were the ankle dorsiflexion and plantar flexion RoMs, which were less than  $20^\circ$  and  $45^\circ$ , respectively, since those angles were reported as the normal ranges of ankle joint motion in the Japanese population (Yonemoto et al., 1995). The sample size needed for two-way repeated measures analysis of variance (ANOVA) was calculated using G\*Power 3.1 (Heinrich Heine University, Düsseldorf, Germany). The calculation was performed with an effect size  $f$  of 0.40 [large], because a change in RoM as a result of SS with the ankle dorsiflexed showed a large effect ( $d = 0.73$ ; RoM, before and after SS,  $92.5 \pm 16.5^\circ$  and  $104.5 \pm 17.7^\circ$ , respectively) in the previous study (Laudner et al., 2016) and a power of 0.8 at an alpha level of 0.05, thereby resulting in 14 participants. All participants were fully informed about the purpose of this study as well as its procedures and provided informed consent before participating in the experiments. Ethical approval was granted by our institutional ethics committee.

### 2.3. Static stretching protocol

The participants performed SS for the hamstrings of the dominant leg, which was defined as the leg preferred to kick a ball. The participants lay in a supine position with the pelvis anteriorly inclined by placing a wedge between the pelvis and the bed, and the nondominant leg was fixed with the knee and hip extended by a belt (Nakao et al., 2019; Umegaki et al., 2015). The ankle was fixed at  $20^\circ$  dorsiflexion for SS with the ankle dorsiflexed and  $45^\circ$  plantar flexion for SS with the ankle plantar-flexed using a double upright ankle-foot orthosis and a wedge insole. These angles were selected because it has been reported that the normal range of ankle joint motion of the Japanese population is  $20^\circ$  dorsiflexion and  $45^\circ$  plantar flexion (Yonemoto et al., 1995). Keeping the knee at full extension, the hip was passively flexed until the point just before the participant felt stretching pain (Fig. 2), and this position was maintained for 1 min. The 1-min SS was performed for 5 sessions with a 30-s rest between sessions because previous studies have reported that passive stiffness decreased after 5-min SS (Matsuo et al., 2013; Umegaki et al., 2015). Hip flexion angle during SS was measured using a 30-cm long-arm goniometer by a physical therapist with over 5 years of clinical experience. The average of hip flexion angles in the 5 sessions was used for analysis. The investigators who measured hip flexion angles were not informed about which SS (SS with the ankle dorsiflexed or plantar-flexed) the participant performed.

### 2.4. Measurements of the final angle, passive torque at the final angle, and passive stiffness

The participants lay in a supine position with the pelvis anteriorly tilted by putting a wedge between the pelvis and the bed. The

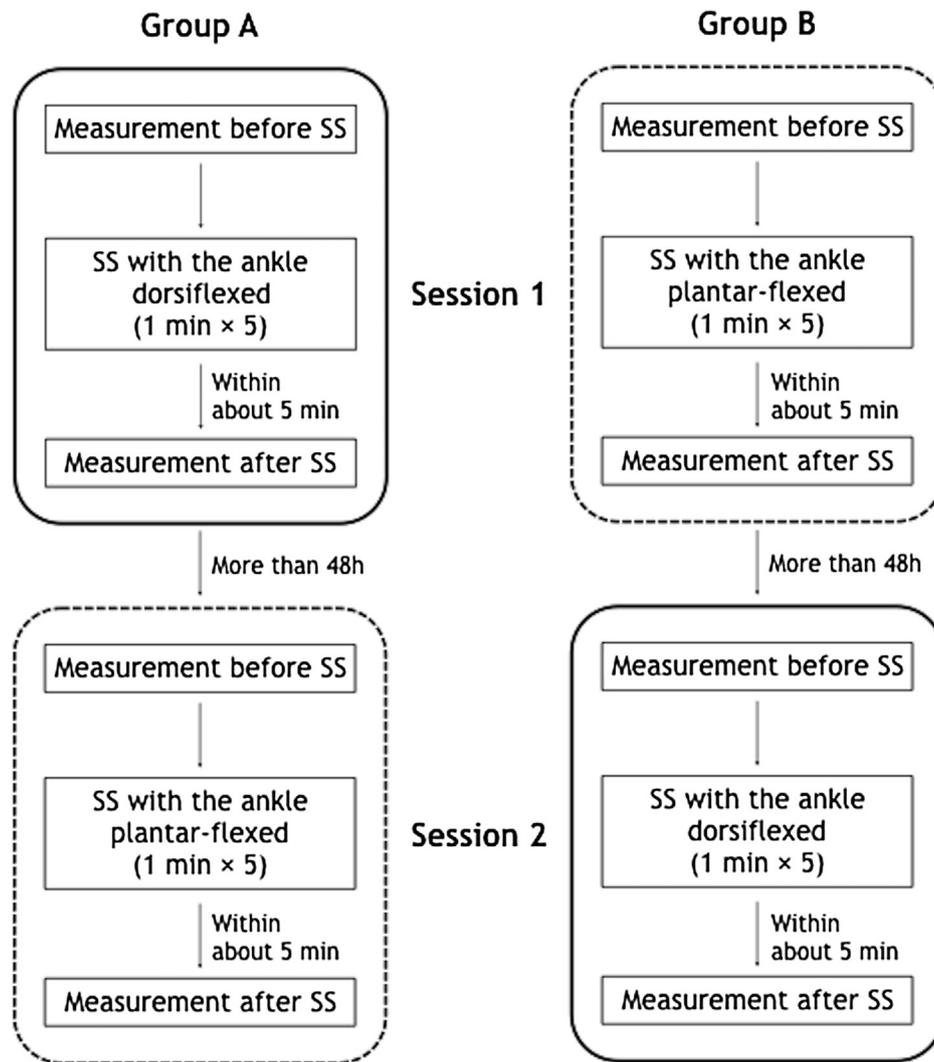
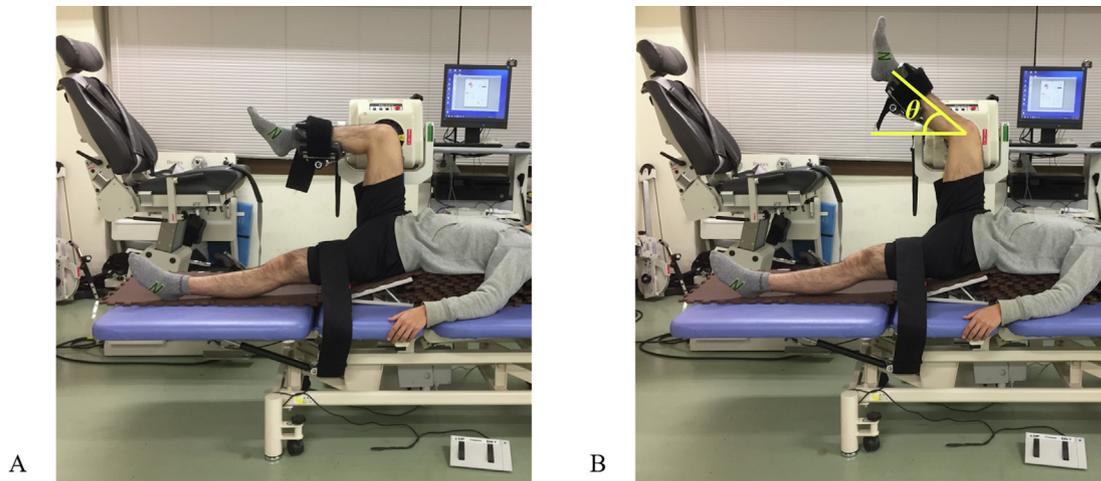


Fig. 1. Flowchart of the study. SS: static stretching.

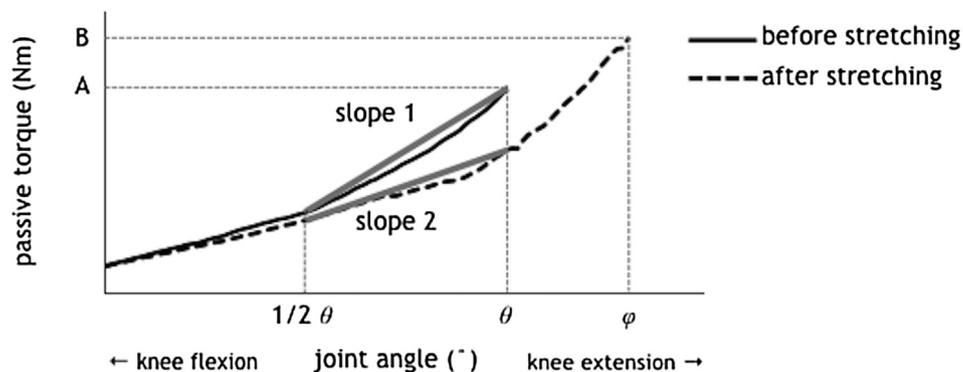


Fig. 2. Static stretching (SS) position when performing SS with the ankle dorsiflexed: the ankle was fixed at 20° dorsiflexion using a double upright ankle-foot orthosis.

dominant lower leg was attached to a dynamometer (Biodex System 4.0, Biodex Medical Systems, Inc., NY, USA) with the hip and knee angles set at 90° flexion. The nondominant leg was fixed with the knee and hip extended by a belt (Fig. 3) (Nakao et al., 2019; Umegaki et al., 2015). From this position, the knee was passively extended at 5°/s of constant velocity using the dynamometer, thereby obtaining the passive torque-angle curve to calculate the final angle, passive torque at the final angle, and passive stiffness (Fig. 4). The participants were asked to push a stop button of the dynamometer when the knee reached the maximum angle that they could tolerate without a stretch pain. This knee extension angle was recorded as the final angle, which was expressed as the change in the knee angle from 90° flexion. The participants were instructed to relax; therefore, their ankles were plantar-flexed freely during the measurement. Passive stiffness was determined by the slope of torque-angle curve during passive knee extension (i.e., the value obtained by dividing the amount of change in passive torque by the change in knee angle). Based on previous studies (Matsuo et al., 2013; Nakao et al., 2019), the knee joint range used for the calculation of passive stiffness was from 50% to 100% of the minimum final angle before SS, and the same joint range was used for the calculation before and after SS (Fig. 4). Measurements were repeated two times each before and after SS. The average of two



**Fig. 3.** Positions for the measurement of the final angle, passive torque at the final angle, and passive stiffness. A: Starting position of the measurements. B: The knee was passively extended until the point just before the participant felt stretching pain (final angle).  $\theta$  was defined as the final angle.



**Fig. 4.** Representative passive-torque curve during passive knee extension before and after static stretching (SS).  $\theta$ : final angle before SS.  $\phi$ : final angle after SS. A: passive knee flexion torque at  $\theta$ . B: passive knee flexion torque at  $\phi$ . Slope 1: passive stiffness before SS. Slope 2: passive stiffness after SS.

measurements was used for statistical analysis to compare the final angle, passive torque at the final angle, and passive stiffness before and after SS. The measurements after SS were performed in about 5 min after the last session. The measurement is considered complete within the time at which the stretching effects lasted, since the previous study reported that changes in RoM, passive torque at RoM, and passive stiffness lasted for between 20 and 30 min (Hatano et al., 2019).

The reliability of the measurements was assessed by calculating intraclass correlation coefficients (ICCs) using two values measured before SS in the first session. The ICC(1,2) values for the final angle, passive torque at the final angle, and passive stiffness were 0.981, 0.991, and 0.843, respectively.

### 2.5. Statistical analysis

The normality of the data was confirmed using Shapiro-Wilk test. A paired *t*-test was used to compare hip flexion angles during SS with the ankle dorsiflexed and SS with the ankle plantar-flexed. Two-way repeated measures ANOVA using time (before and after SS) and ankle position (dorsiflexion and plantar flexion) as the two factors was used to determine the effects of SS with the ankle dorsiflexed and SS with the ankle plantar-flexed on the final angle, passive torque at the final angle, and passive stiffness. SPSS version 22.0 (SPSS Japan Inc., Tokyo, Japan) was used for all statistical analyses, with the significant level set at 0.05. Descriptive data are presented as mean  $\pm$  standard deviation.

### 3. Results

Mean hip flexion angles during SS were  $53.7 \pm 8.7^\circ$  and  $69.3 \pm 12.6^\circ$  for SS with the ankle dorsiflexed and SS with the ankle plantar-flexed, respectively. The paired *t*-test showed that hip flexion angle was significantly lower for SS with the ankle dorsiflexed than for SS with the ankle plantar-flexed ( $P < 0.01$ ).

The final angle, passive torque at the final angle, and passive stiffness are presented in Table 1. For the final angle, two-way repeated measures ANOVA showed no significant time  $\times$  ankle position interaction. With respect to the main effect of time or ankle position, only a significant main effect of time was observed ( $P < 0.01$ ), indicating that the final angle significantly increased after SS regardless of the ankle position during SS. For the passive torque at the final angle, two-way repeated measures ANOVA showed no significant interaction, and only a significant main effect of time was observed ( $P < 0.01$ ), suggesting that the passive torque at the final angle also increased after SS regardless of the ankle position. For passive stiffness, two-way repeated measures ANOVA showed a significant interaction ( $P < 0.05$ ). Post hoc analysis showed a significant decrease in passive stiffness after SS with the ankle plantar-flexed ( $P < 0.01$ ) but not after SS with the ankle dorsiflexed.

### 4. Discussion

The present study compared the effects of SS with the ankle dorsiflexed and SS with the ankle plantar-flexed for the hamstrings

**Table 1**

Final angle, passive torque at the final angle, and passive stiffness.

	SS with the ankle dorsiflexed		SS with the ankle plantar-flexed		Average	
	Before SS	After SS	Before SS	After SS	Before SS	After SS
Final angle (°)	70.5 ± 16.7	81.3 ± 17.6	70.9 ± 16.7	83.5 ± 18.2	70.7 ± 16.4	82.4 ± 17.6 <sup>†</sup>
Passive torque at the final angle (Nm)	40.8 ± 10.8	44.5 ± 11.1	41.2 ± 10.7	42.7 ± 10.4	41.0 ± 10.6	43.6 ± 10.6 <sup>†</sup>
Passive stiffness (Nm/°)	0.45 ± 0.13	0.44 ± 0.14	0.47 ± 0.13	0.39 ± 0.14*	0.46 ± 0.13	0.42 ± 0.14

Values are expressed as mean ± standard deviation.

SS, static stretching.

<sup>†</sup> There were no interaction but significant time effect for the final angle and passive torque at the final angle.

\* There was significant interaction and a simple effect of time was showed only in SS with the ankle plantar-flexed for passive stiffness.

on RoM and passive stiffness. The results showed that the final angle and passive torque at the final angle significantly increased after SS regardless of the ankle position and that passive stiffness significantly decreased after SS with the ankle plantar-flexed but not after SS with the ankle dorsiflexed. To the best of our knowledge, this is the first study that showed that the effect of SS for the hamstrings on passive stiffness was affected by the ankle position during SS.

The final angle (i.e., RoM) significantly increased after 5-min SS regardless of the ankle position, which was consistent with the results of a previous study (Laudner et al., 2016) and supported our hypothesis. Passive torque at the final angle, which was used as an indicator of stretch tolerance (Halbertsma et al., 1996), also significantly increased after SS regardless of the ankle position. In this study, SS was performed at the maximum tolerated hip flexion angle without stretching pain so that the subjective stretching intensity was the same. The results suggest that similar effects on stretch tolerance, i.e., similar increase in stretch pain thresholds, are obtained regardless of the ankle position when the subjective intensity of SS is the same.

The results of this study showed that a significant change in passive stiffness was observed after SS with the ankle plantar-flexed but not after SS with the ankle dorsiflexed, which supported our hypothesis. The results suggest that passive stiffness of the hamstrings does not change after 5-min SS with the ankle dorsiflexed but decreases after SS with the ankle plantar-flexed. The reason why passive stiffness did not decrease after SS with the ankle dorsiflexed could be explained by the hip flexion angle during SS with the ankle dorsiflexed being lower than that during SS with the ankle plantar-flexed. Previous studies indicated that hip flexion angle during passive SLR with the ankle dorsiflexed was significantly lower than that with the ankle plantar-flexed (Gajdosik et al., 1985; Palmer et al., 2015). Such a restriction of hip flexion angle can be explained by an increase in sciatic nerve tension with the ankle dorsiflexed (Andrade et al., 2016b). Another study reported that a larger joint angle at which SS was performed induced a larger decrease in passive torque after SS (Freitas et al., 2015). Based on these studies, the results of the present study indicated that hip flexion angle during SS with the ankle dorsiflexed is restricted by sciatic nerve tension rather than passive tension of the hamstring muscles, resulting in insufficient stretching for the passive stiffness because of the lack of passive tension to the hamstrings.

Two reasons can be considered why the final angle increased after both SS while passive stiffness decreased only after SS with the ankle plantar-flexed. First, passive torque at the final angle (i.e., stretch tolerance) might attribute greater than passive stiffness to a change in the final angle (i.e., RoM). It has been reported that an increase in RoM was affected by both stretch tolerance and passive stiffness (Matsuo et al., 2013; Mizuno et al., 2013). However, considering that many previous studies indicated that RoM and passive torque at RoM increased while passive stiffness did not change as acute or chronic effects of SS (Halbertsma et al.,

1996; Halbertsma and Goeken, 1994), attribution of stretch tolerance might be greater than passive stiffness to a change in RoM. Second, in the present study, while there was no significant time × ankle position interaction in stretch tolerance, an effect size of difference in stretch tolerance was greater for SS with the ankle dorsiflexed than plantar-flexed (Cohen's  $r = 0.77$  and  $0.36$ , respectively). Therefore, the results of the present study could be interpreted to mean that even when passive stiffness indicated greater decrease after SS with the ankle plantar-flexed than SS with the ankle dorsiflexed, due to less increase in stretch tolerance, a similar increase in RoM may be generated after both SS.

It is believed that SS reduces passive stiffness or increases compliance of the musculotendinous unit; thereby, contributing to the prevention of strain injury (McHugh and Cogrove, 2010). As a potential mechanism of decreasing passive stiffness or increasing musculotendinous unit compliance, it is considered that the increase in muscle length (sarcomere number) or redistribution of liquid and polysaccharides within the collagen matrix could be involved (Boakes et al., 2007; McNair et al., 2001; Williams and Goldspink, 1973). Previous studies stated that if the musculotendinous unit were more compliant, the torque–angle relationship was shifted to the right (Nakao et al., 2019), which indicated that the portion of the descending limb of the force–length curve was decreased. It has been reported that muscle damage likely occurred during eccentric contractions on the descending limb of the force–length curve, that is, the portion that corresponds to longer muscle length than optimal length, where the muscle would be lengthened nonuniformly (Morgan, 1990; Morgan and Allen, 1999; Timmins et al., 2016). Therefore, it is believed that increasing compliance (reducing passive stiffness) of the musculotendinous unit by SS is helpful for prevention of hamstring strain injuries (McHugh and Cogrove, 2010). Other review articles have also suggested that SS might reduce injuries in sports with high stretch-shortening cycle movements, because more compliant musculotendinous units can absorb more elastic energy (Opar et al., 2012; Witvrouw et al., 2004). Since passive stiffness decreased only after SS with the ankle plantar-flexed in the present study, SS with the ankle plantar-flexed may be more effective in injury prevention than SS with the ankle dorsiflexed. Further study is needed to clarify the chronic effect of SS and relationship between both SS and injury prevention.

The present study has some limitations. First, the prolonged effect after SS remains unclear in the present study. A previous study reported that the effects of 5-min hamstring stretching lasted for 30 min regarding RoM and passive torque at RoM and 20 min regarding passive stiffness (Hatano et al., 2019). Therefore, it is assumed that the effects of SS in the current study may also last for about 20 or 30 min. Further study is needed to investigate how long the effect of stretching lasts and whether the effects would be different depending on ankle position during stretching. Second, blinding would be insufficient because all outcome measurements and analyses, except for those of the hip flexion angles during SS, were performed by the same investigator. However, it is

considered that there was low measurement bias in this study as the measurements of the final angle, passive torque at the final angle, and passive stiffness were performed with the protocol programmed in the dynamometer. Another potential limitation is that muscle activity was not monitored by electromyography to ensure that the stretching and measurements were performed indeed passively in this study. However, it is assumed that the stretching and measurements were performed without muscle contraction because the hip angle was set at the angle just before the participants felt stretch pain and the measurements were performed at slow velocity (5°/s) thereby preventing stretch reflex activity (Hufschmidt and Mauritz, 1985).

## 5. Conclusions

The present study investigated the effects of 5-min SS with the ankle dorsiflexed and SS with the ankle plantar-flexed for the hamstrings, both with the same subjective intensity. The results showed that RoM and stretch tolerance increased regardless of the ankle position during SS; however, passive stiffness decreased only after SS with the ankle plantar-flexed. The results suggest that SS for the hamstrings should be performed with the ankle plantar-flexed, not dorsiflexed, when aiming to decrease passive stiffness.

## Declaration of Competing Interest

The authors declare no conflicts of interest related to the manuscript.

## Acknowledgements

We would like to thank Ms. Ibuki and Editage ([www.editage.jp](http://www.editage.jp)) for English language editing. This work was supported by JSPS KAKENHI Grant Number JP 15H03043 [Grant-in-Aid for Scientific Research (B)], Japan.

## References

- Andrade, R.J., Lacourpaille, L., Freitas, S., McNair, P.J., Nordez, A., 2016a. Effects of hip and head position on ankle range of motion, ankle passive torque, and passive gastrocnemius tension. *Scand. J. Med. Sci. Sports* 26, 41–47.
- Andrade, R.J., Nordez, A., Hug, F., Ates, F., Coppieters, M.W., Pezarat-Correia, P., Freitas, S.R., 2016b. Non-invasive assessment of sciatic nerve stiffness during human ankle motion using ultrasound shear wave elastography. *J. Biomech.* 49, 326–331.
- Bandy, W.D., Irion, J.M., 1994. The effect of time on static stretch on the flexibility of the hamstring muscles. *Phys. Ther.* 74, 845–850.
- Bandy, W.D., Irion, J.M., Briggler, M., 1997. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys. Ther.* 77, 1090–1096.
- Bandy, W.D., Irion, J.M., Briggler, M., 1998. The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. *J. Orthop. Sports Phys. Ther.* 27, 295–300.
- Ben, M., Harvey, L.A., 2010. Regular stretch does not increase muscle extensibility: a randomized controlled trial. *Scand. J. Med. Sci. Sports* 20, 136–144.
- Boakes, A.L., Foran, J., Ward, S.R., Lieber, R.L., 2007. Muscle adaptation by serial sarcomere addition 1 year after femoral lengthening. *Clin. Orthop. Relat. Res.* 456, 250–253.
- Bradley, P.S., Portas, M.D., 2007. The relationship between preseason range of motion and muscle strain injury in elite soccer players. *J. Strength Condit. Res.* 21, 1155–1159.
- Brooks, J.H.M., Fuller, C.W., Kemp, S.P., Reddin, D.B., 2006. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am. J. Sports Med.* 34, 1297–1306.
- Castellote-Caballero, Y., Valenza, M., Puenteadura, E., Fernández-de-Las-Peñas, C., Alburquerque-Sendín, F., 2014. Immediate effects of neurodynamic sliding versus muscle stretching on hamstring flexibility in subjects with short hamstring syndrome. *J. Sports Med. (Hindawi Publish. Corpor.)* 29, 865–871.
- Decoster, L.C., Cleland, J., Altieri, C., Russell, P., 2005. The effects of hamstring stretching on range of motion: a systematic literature review. *J. Orthop. Sports Phys. Ther.* 35, 377–387.
- Fasen, J.M., O'Connor, A.M., Schwartz, S.L., Watson, J.O., Plastaras, C.T., Garvan, C.W., Bulcao, C., Johnson, S.C., Akuthota, V., 2009. A randomized controlled trial of hamstring stretching: comparison of four techniques. *J. Strength Condit. Res.* 23, 660–667.
- Feeley, B.T., Kennelly, S., Barnes, R.P., Muller, M.S., Kelly, B.T., Rodeo, S.A., Warren, R. F., 2008. Epidemiology of National football league training camp injuries from 1998 to 2007. *Am. J. Sports Med.* 36, 1597–1603.
- Freitas, S.R., Vilarinho, D., Rocha Vaz, J., Bruno, P.M., Costa, P.B., Mil-homens, P., 2015. Responses to static stretching are dependent on stretch intensity and duration. *Clin. Physiol. Funct. Imag.* 35, 478–484.
- Gajdosik, R.L., Leveau, B.F., Bohannon, R.W., 1985. Effects of ankle dorsiflexion on active and passive unilateral straight leg raising. *Phys. Ther.* 65, 1478–1482.
- Halbertsma, J.P.K., Goeken, L.N.H., 1994. Stretching exercises: effect on passive extensibility and stiffness in short hamstrings on healthy subjects. *Arch. Phys. Med. Rehabil.* 75, 976–981.
- Halbertsma, J.P.K., vanBolhuis, A.I., Goeken, L.N.H., 1996. Sport stretching: effect on passive muscle stiffness of short hamstrings. *Arch. Phys. Med. Rehabil.* 77, 688–692.
- Hatano, G., Suzuki, S., Matsuo, S., Kataura, S., Yokoi, K., Fukaya, T., Fujiwara, M., Asai, Y., Iwata, M., 2019. Hamstring stiffness returns more rapidly after static stretching than range of motion, stretch tolerance, and isometric peak torque. *J. Sport Rehab.* 28, 325–331.
- Hufschmidt, A., Mauritz, K.H., 1985. Chronic transformation of muscle in spasticity: a peripheral contribution to increased tone. *J. Neurol. Neurosurg. Psych.* 48, 676–685.
- Laudner, K.G., Benjamin, P.J., Selkow, N.M., 2016. Effect of ankle positioning during hamstring stretches for improving straight leg hip flexion motion. *Clin. J. Sport Med.* 26, 167–171.
- Magnusson, S.P., Simonsen, E.B., Aagaard, P., Kjaer, M., 1996. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. *Am. J. Sports Med.* 24, 622–628.
- Marshall, P.W.M., Cashman, A., Cheema, B.S., 2011. A randomized controlled trial for the effect of passive stretching on measures of hamstring extensibility, passive stiffness, strength, and stretch tolerance. *J. Sci. Med. Sport* 14, 535–540.
- Matsuo, S., Suzuki, S., Iwata, M., Banno, Y., Asai, Y., Tsuchida, W., Inoue, T., 2013. Acute effects of different stretching durations on passive torque, mobility, and isometric muscle force. *J. Strength Condit. Res.* 27, 3367–3376.
- McHugh, M.P., Kremenik, I.J., Fox, M.B., Gleim, G.W., 1998. The role of mechanical and neural restraints to joint range of motion during passive stretch. *Med. Sci. Sports Exerc.* 30, 928–932.
- McHugh, M.P., Cosgrave, C.H., 2010. To stretch or not to stretch: the role of stretching in injury prevention and performance. *Scand. J. Med. Sci. Sports* 20, 169–181.
- McNair, P.J., Dombroski, E.W., Hewson, D.J., Stanley, S.N., 2001. Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. *Med. Sci. Sports Exerc.* 33, 354–358.
- Mizuno, T., Matsumoto, M., Umemura, Y., 2013. Viscoelasticity of the muscle-tendon unit is returned more rapidly than range of motion after stretching. *Scand. J. Med. Sci. Sports* 23, 23–30.
- Morgan, D.L., 1990. New insights into the behavior of muscle during active lengthening. *Biophys. J.* 57, 209–221.
- Morgan, D.L., Allen, D.G., 1999. Early events in stretch-induced muscle damage. *J. Appl. Physiol.* 87, 2007–2015.
- Nakao, S., Ikezoe, T., Nakamura, M., Umegaki, H., Fujita, K., Umehara, J., Kobayashi, T., Ibuki, S., Ichihashi, N., 2019. Chronic effects of a static stretching program on hamstring strength. *J. Strength Condit. Res.* 23 [Epub ahead of print].
- Opar, D.A., Williams, M.D., Shield, A.J., 2012. Hamstring strain injuries: factors that lead to injury and re-injury. *Sports Med.* 42, 209–226.
- Orchard, J.W., Seward, H., Orchard, J.J., 2013. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am. J. Sports Med.* 41, 734–741.
- O'Sullivan, K., Murray, E., Sainsbury, D., 2009. The effect of warm-up, static stretching and dynamic stretching on hamstring flexibility in previously injured subjects. *BMC Musculoskel. Disorders* 10, 37.
- Palmer, T.B., Akehi, K., Thiele, R.M., Smith, D.B., Warren, A.J., Thompson, B.J., 2015. Dorsiflexion, plantar-flexion, and neutral ankle positions during passive resistance assessments of the posterior hip and thigh muscles. *J. Athletic Train.* 50, 467–474.
- Sullivan, M.K., DeJulia, J.J., Worrell, T.W., 1992. Effect of pelvic position and stretching method on hamstring muscle flexibility. *Med. Sci. Sports Exerc.* 24, 1383–1389.
- Timmins, R.G., Shield, A.J., Williams, M.D., Opar, D.A., 2016. Is there evidence to support the use of the angle of peak torque as a marker of hamstring injury and re-injury risk? *Sports Med.* 46, 7–13.
- Umegaki, H., Ikezoe, T., Nakamura, M., Nishishita, S., Kobayashi, T., Fujita, K., Tanaka, H., Ichihashi, N., 2015. Acute effects of static stretching on the hamstrings using shear elastic modulus determined by ultrasound shear wave elastography: differences in flexibility between hamstring muscle components. *Manual Ther.* 20, 610–613.
- Verrall, G.M., Kalairajah, Y., Slavotinek, J.P., Spriggins, A.J., 2006. Assessment of player performance following return to sport after hamstring muscle strain injury. *J. Sci. Med. Sport* 9, 87–90.

- Williams, P.E., Goldspink, G., 1973. Effect of immobilization on longitudinal growth of striated muscle fibers. *J. Anat.* 116, 45–55.
- Witvrouw, E., Danneels, L., Asselman, P., D'Have, T., Cambier, D., 2003. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *Am. J. Sports Med.* 31, 41–46.
- Witvrouw, E., Mahieu, N., Danneels, L., McNair, P., 2004. Stretching and injury prevention: an obscure relationship. *Sports Med.* 34, 443–449.
- Ylinen, J., Kankainen, T., Kautiainen, H., Rezasoltani, A., Kuukkanen, T., Häkkinen, A., 2009. Effect of stretching on hamstring muscle compliance. *J. Rehabil. Med.* 41, 80–84.
- Yonemoto, K., Ishigami, S., Kondo, T., 1995. Display and measurement of range of joint motion. *Jpn. J. Rehab. Med.* 32, 207–217.