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博　士　論　文

Effects of long-term self-massage at the musculotendinous junction on hamstring extensibility, stiffness, stretch tolerance, and structural indices: a randomized controlled trial

（ハムストリングス筋腱移行部への長期的なセルフマッサージがハムストリングス伸張性，柔軟性，ストレッチ耐性および構造学的指標に与える効果：無作為化比較対照試験）

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Contents

Abstract

Objectives

The purpose of this study was to examine the effect of long-term self-massage at the musculotendinous junction on hamstring extensibility, stiffness, stretch tolerance, and structural indices.

Design

Single-blind, randomized, controlled trial.

Setting

Laboratory.

Participants

Thirty-seven healthy men.

Intervention

The right or left leg of each participant was randomly assigned to the massage group, and the other leg was assigned to the control group. The participants conducted self-massage at the musculotendinous junction for 3 minutes daily, five times per week, for 12 weeks.

Main Outcome Measures

Hamstring extensibility, stiffness, stretch tolerance, and structural indices were measured by a blinded examiner prior to the massage intervention and after 6 and 12 weeks of intervention.

Results

The maximum hip flexion angle (HFA) and the maximum passive pressure after 6 and 12 weeks of intervention in the massage group were significantly higher than prior to intervention. The visual analog scale (for pain perception) at maximum HFA, the stiffness of the hamstring, and the structural indices did not differ in either group over the 12 week period.

Conclusions

Our results suggest that long-term self-massage at the musculotendinous junction increases hamstring extensibility by improving stretch tolerance. However, this intervention does not change hamstring stiffness.

Key words

hamstring extensibility, stretch tolerance, self-massage, musculotendinous junction

1. Introduction

Good hamstring extensibility and optimal stiffness is needed for sport but also functional activity (Bradley & Portas, 2007; McHugh, Connolly, & Eston, 1999; Witvrouw, Danneels, & Asselman, 2003; Ylinen, Kankainen, & Kautiainen, 2009). In sport setting, massage is used frequently in order to increase hamstring extensibility (Bradley & Portas, 2007; Hopper, Conneely & Chromiak, 2005a; McHugh, Connolly, & Eston, 1999; Witvrouw, Danneels, & Asselman, 2003). However, in previous studies (Akazawa, Harada, & Okawa, 2013; Barlow, Clarke, & Johnson, 2004; Hopper, Conneely, & Chromiak, 2005a; Hopper, Deacon, & Das, 2005b; Huang, Di santo, & Wadden, 2010; Wiktorsson-Möller, Oberg, & Ekstrand, 1983), the effects of massage on hamstring extensibility is controversial.

To date, the effects of massage on hamstring extensibility have been examined. Although a single 6- to 15-minute massage of the entire hamstring did not change extensibility (Barlow et al., 2004; Hopper et al., 2005a; Wiktorsson-Möller et al., 1983), Hopper et al. (2005b) reported that 8 minutes of dynamic soft tissue mobilization significantly increased hamstring extensibility which measured with hip flexion angle (HFA). However, in their study, the passive pressure during the measurement of HFA was not standardized. Passive range of motion measured with non-standardized passive pressure can fluctuate with changes in stretch tolerance (Halbertsma and Göeken, 1994; Magnusson, Simonsen, & Aagaard, 1996). Massage at the musculotendinous junction may be more effective than massage over the entire muscle; in 2010, Huang et al. reported that the HFA after 30-seconds of friction massage was significantly higher than after a non-massage period. In 2013, we examined the effects of 3-minute hamstring massages at either the musculotendinous junction or the muscle belly on HFA (Akazawa et al., 2013). We found that the HFA of the group that received musculotendinous junction massage was significantly higher than that of the control group, while the HFA of the group that received muscle belly massage did not differ from that of the controls.

Taken together, the results obtained by Huang et al. (2010) and ourselves (Akazawa et al., 2013) indicate that a single massage at the musculotendinous junction increases hamstring extensibility. Based on electromyographic measurements, Huang et al. (2010) hypothesized that this effect may be attributed to decreased excitability of spinal motor neurons. In 2013, Behm et al. demonstrated that the decrease in spinal motor neuron excitability seen after massage lasted less than 1 minute after the intervention. Considering these results, the increase of hamstring extensibility resulting from a single massage may be insufficient to improve sports performance because the competition time of most sports requires more than 1 minute of play. However, whether long-term massage at the musculotendinous junction increases hamstring extensibility for a longer period of time is not known.

The effect of massage on hamstring stiffness has not yet been examined. Moreover, muscle structure may also affect the effects of massage on stiffness. Recently, some static stretching (SS) intervention studies examined the influence of muscle structure on changes in muscle stiffness using ultrasonography (Morse, Degens, & Seynnes, 2008; Nakamura, Ikezoe, & Takeno, 2012). The results of these studies suggested that decrease of muscle stiffness caused by SS intervention was associated with change in connective tissue but not muscle structure. However, this technique has not yet been used to study the effects of muscle structure on massage outcomes.

The purpose of this study was to clarify the effects of long-term and self-massage at the musculotendinous junction on hamstring extensibility, stiffness, stretch tolerance, and structural indices. Weppler & Magnusson (2010) defined that extensibility means the ability of a muscle to extend to an endpoint, and that stiffness means the change in tension per unit change in muscle length. Then, in this study we followed these definitions.

2. Materials and Methods

2.1. Participants

Thirty-seven men participated in this study. Participants were students from a single university. We recruited them using advertisement. Potential participants who had orthopedic disorders, neurological disorders, and the excessive hamstring extensibility were excluded (Ben & Harvey, 2010; Folpp, Deall, & Harvey, 2006; Law, Harvey, & Nicholas, 2009). The excessive hamstring extensibility was defined as being able to place the palms of the hands flat on the floor during the standard toe-touch test (Ben & Harvey, 2010; Folpp et al., 2006; Gauvin, Riddle, & Rothstein, 1990; Law et al., 2009). None of the participants were competitive athletes or were engaged in systematic resistance training or stretching programs. All participants were instructed not to start any new forms of training during the study period, although they were permitted to continue their current exercise regimes. The characteristics of the subjects are presented in Table 1.

In our previous study (Akazawa et al., 2013), the mean difference of the change in HFA between the massage and control groups was 5.9°. Importantly, 5° has been reported to be the minimum clinically significant difference (Ben & Harvey, 2010; Folpp et al., 2006; Law et al., 2009). To estimate the required sample size for the current study, we estimated that the effect size of long-term self-massage at the musculotendinous junction would be the same as that of a single massage at the musculotendinous junction (d = 0.97) in our previous study (Akazawa et al., 2013), because we expected a clinically detectable difference in HFA between the massage and control groups. Rate of α, power (1 - β), and dropout were set at 5, 95, and 15% (Folpp et al., 2006), respectively. The statistical power calculation indicated that 35 legs per group were needed to maintain sufficient statistical power.

Each participant provided their written informed consent. The study protocol was approved by the Ethics Committee of Kobe University. This trial was registered to the University Hospital Medical Information Network (UMIN) center (registration number UMIN000011233) prior to commencement.

2.2. Study design

A single-blind, randomized, controlled trial with a within-subject design (Ben & Harvey, 2010; Folpp et al., 2006; Law et al., 2009) was used in this study. Either the right or the left leg of each participant was randomly assigned to the massage group, and the other leg was assigned to the control group. This design minimizes between-group variability, which can be influenced by personal factors such as exercise and activity patterns (Akagi & Takahashi, 2014; Ben & Harvey, 2010; Folpp et al., 2006; Law et al., 2009). We asked people who were not otherwise involved in the study to do the random allocation. They performed the randomization with random number generated by computer. Moreover, the principal investigator and all assessors were not aware of the randomization methods.

2.3. Self-massage at the musculotendinous junction

The participants were taught to perform self-massage at the musculotendinous junction, four finger widths proximal to the medial and lateral epicondyles of the femur, using their fingertips while in a sitting positon (Figure 1). The massage technique was one-handed petrissage, which consists of grasping, lifting, and releasing, at a rate of 0.5 Hz (Goldberg, Sullivan, & Seaborne, 1992; Goldberg, Seaborne, & Sullivan, 1994) with 2.5 kPa of pressure (Goldberg et al., 1992). This technique has been shown to decrease the excitability of spinal motor neurons (Goldberg et al., 1992; Goldberg et al., 1994). In this study, massage pressure was converted from 2.5 kPa to 18.7 mmHg. Participants performed self-massage for 3 minutes per day, five days per week, for 12 weeks.

To ensure accurate reproduction of the required massage pressure and rate, the participants practiced massaging the manchette of a sphygmomanometer with a pressure of 100 to 118.7 mmHg with pace of one time per 2 seconds prior to the intervention, and more than once per week during the study period. Participants were asked to record these training sessions and the massage sessions in a diary. The control limbs were not massaged during the study period. In a recent review summarizing the effects of SS on hamstring extensibility (Weppler & Magnusson, 2010), a 3- to 8-week intervention period was defined as "short-term", whereas an intervention period of more than 8 weeks was defined as "long-term". In accordance with this definition (Weppler & Magnusson, 2010), we defined the 12-week intervention period in this study as "long-term".

2.4. Outcome measures

HFA and passive pressure were measured at maximum HFA and at standardized pressures in order to determine whether maximum HFA, hamstring stiffness or stretch tolerance were altered. In addition, we measured stiffness of muscle-tendon unit, musculotendinous junction and muscle belly, and structural index of the hamstrings. All outcomes were measured by a blinded examiner prior to the massage intervention, and after 6 and 12 weeks of massage.

Immediately before the measurements, the participants were asked to walk for

3 minutes at their usual speed, and then to rest for one minute in a supine position. The measurements were started after the rest period. The measurements after 6 and 12 weeks of intervention were taken at least 24 hours after the last massage to reflect the long-term effects of the intervention and exclude acute effects (Akagi & Takahashi, 2014; Ben & Harvey, 2010; Folpp et al., 2006; Law et al., 2009).

2.5. Maximum HFA, maximum passive pressure, standardized HFA, and visual analog scale of the maximum HFA

The HFA was measured with the participant in a relaxed supine position. The thigh of the leg not being measured was firmly fixed to the bed with a band. The measurement leg, with the knee fully extended, was gradually raised by an assessor so as not to elicit the stretch reflex until the angle at which the participants felt pain in the hamstring. This angle was defined as the maximum HFA (Akazawa et al., 2013; Bandy et al., 1997; Huang, Santo, & Wadden, 2010). Moreover, three blinded examiners confirmed that there was no knee flexion of the tested leg and pelvic rotation during testing procedures. The maximum passive pressure (N) was measured at the maximum HFA with a handheld dynamometer (micro FET2, Hoggan Health Industries, Salt Lake, USA) positioned on the calcaneal tuberosity (Figure 2).

Standardized HFA was measured after 6 and 12 weeks of the massage intervention using the maximum passive pressure measured prior to the intervention. In this study, the standardized HFA was considered an index of the stiffness of the longitudinal axis of the hamstring (Ben & Harvey, 2010; Folpp et al., 2006; Law et al., 2009). Fifteen mm diameter colored markers were placed over the greater trochanter and the lateral epicondyle of the femur and the line between them was defined as "the femur". The maximum HFA and the standardized HFA were measured between "the femur" and the plane of the bed, which was parallel to the torso (Akazawa et al., 2013; Huang et al., 2010). The participant was photographed using a digital camera (IXY 200F, Canon, Tokyo, Japan) fixed on a tripod, and maximum HFA and standardized HFA were determined from the image using open source image analysis software (Image J, National Institutes of Health, USA) with a 0.1° unit of measurement. Intraclass correlation coefficients (ICC) of the maximum HFA, standardized HFA, and maximum passive pressure, using measurements taken 6 weeks apart, were 0.966, 0.963, and 0.955, respectively (n = 10). These ICCs indicate that these measurements were highly reliable. The severity of the pain perceived by the participant at the maximum HFA was assessed using a 100 mm visual analog scale (VAS) (Bijur, Silver, & Gallagher, 2001). In the 100 mm VAS, a horizontal line represents the range of possible pain severity from “no pain” at the far left to the “worst possible pain” at the far right. The participants were asked to draw a vertical line crossing the horizontal line at the point which best represented the intensity of the pain they experienced during the measurement of the maximum HFA. The VAS score (mm) was calculated by measuring the distance from “no pain” to their mark.

2.6. Stiffness of the muscle-tendon unit calculated from passive torque

The passive torque when the HFA changed from 20 to 50° was calculated by multiplying the passive pressure at HFAs of 20 and 50° by the distance (m) from the greater trochanter to the calcaneal tuberosity. The passive pressures at HFAs of 20 and 50° were measured using a handheld dynamometer positioned on the calcaneal tuberosity, and measurements were taken in the same posture used for the HFA measurement. The HFAs were determined to be 20 and 50° using a large goniometer of our own making; a HFA of 50° can be achieved in healthy populations (Marshall, Mannion, & Murphy, 2009). The passive torque-angle relationship between HFAs of 20 and 50° has been shown to be linear (Marshall et al., 2009; McHugh, Kremenic, & Fox, 1998). Based on previous studies (Marshall, Cashman, & Cheema, 2011; McHugh et al., 1999), the stiffness of the muscle-tendon unit was calculated by dividing the change in the passive torque between HFAs of 20 and 50° by the change in the HFA. In this study, the stiffness of the muscle-tendon unit was used as an index of the stiffness of longitudinal axis of the hamstring (Akagi & Takahashi, 2014; Marshall et al., 2011; McHugh et al., 1999; Nakamura et al., 2012). The ICC of the measurement of the stiffness of the muscle-tendon unit, using measurements taken 6 weeks apart, was 0.920 (n = 10). Therefore, this measurement technique was highly reliable.

2.7. Stiffness of the musculotendinous junction and the muscle belly calculated from the hardness of the musculotendinous junction and muscle belly

We measured the hardness of the musculotendinous junction and the muscle belly at a 50° HFA and in the prone position using a muscle hardness meter (NEUTONE TDM-Z1, TRY-ALL, Chiba, Japan). The hardness of the muscle belly was measured halfway between the medial epicondyle of the tibia and the ischial tuberosity. The hardness of the musculotendinous junction was measured halfway between the medial epicondyle of the tibia and the site where the muscle belly hardness measurement was taken. The muscle hardness represents transverse muscle stiffness (Murayama, Nosaka, & Yoneda, 2000). The values calculated by dividing the difference in the hardness of the musculotendinous junction and the muscle belly at 0 (prone position) and 50° HFA by the change in the HFA were defined as the stiffness of the musculotendinous junction and the muscle belly. The ICCs of the stiffness of the musculotendinous junction and muscle belly, determined using measurements taken 6 weeks apart, were 0.904 and 0.912, respectively (n = 10). Therefore, these measurements have high reliability. These stiffnesses were used as indices of the stiffness of the transverse axis of the hamstring.

2.8. Structural indices of the hamstring (pennation angle, muscle thickness, and muscle fascicle length of the semitendinosus)

B-mode ultrasonography (EUB-7500 HV, Hitachi Medical, Tokyo, Japan) with a 7.5 MHz linear type probe (EUP-L 65, Hitachi Medical, Tokyo, Japan) was used to image the sagittal plane of the semitendinosus muscle halfway between the medial epicondyle of the tibia and the ischial tuberosity at a HFA of 50°. Water soluble transmission gel was applied to the skin surface and the probe was pressed lightly against the skin to avoid deformation of the muscle. The pennation angle of the semitendinosus muscle was determined from the angle of insertion of the fascicle into the deep aponeurosis (Figure 3) (Samukawa, Hattori, & Sugama, 2011). Muscle thickness was defined as the distance between the deep and superficial aponeurosis (Figure 3) (Samukawa et al., 2011). Both the pennation angle and the thickness of the semitendinosus muscle were obtained from ultrasound images that were quantified using open source image analysis software (Image J, National Institutes of Health, USA). The ICCs of the pennation angle and the muscle thickness measurements, using values obtained 6 weeks apart, were 0.921 and 0.957, respectively (n = 10). Therefore, these measurements are highly reliable. The fascicle length was calculated using the following formula (Kumagai, Abe, & Brechue, 2000):

$$\text{Fascicle length} = \text{muscle thickness}/\sin(\text{pennation angle})$$

2.9. Statistical Analysis

Statistical analyses were done using SPSS statistics version 21 (IBM SPSS Japan, Tokyo, Japan). In advance, we confirmed that all variables normally distributed using Shapiro-Wilk test. The significance of pre-existing (before the intervention) differences for all dependent variables were evaluated using unpaired t-tests. Two-way analysis of variance [ANOVA; experimental group (massage group and control group) × test time (prior to intervention, after 6 weeks or 12 weeks of intervention)] was used to assess the significance of the interaction between group and test time. Then, repeated measures ANOVA [test time (prior to intervention, and after 6 weeks or 12 weeks of intervention)] followed by the Bonferroni multiple comparison test was used to investigate the effects of the intervention on all dependent variables. When significant differences were present in the multiple comparison test, 95% confidence intervals (CI) were calculated. Descriptive data in the text, figures, and tables are presented as means ± SD. Statistical significance was set at $p < .05$. The principle of intention-to-treat was used for all analyses.

3. Results

Twenty-one right legs and 16 left legs were allocated to the massage group. No participants withdrew from the study. There were no side effects of the intervention during the study period. We were able to confirm 93.5 ± 0.1% massage compliance rates from the diaries. No significant between-group differences were present at baseline.

3.1. Maximum HFA, maximum passive pressure, standardized HFA, and VAS of maximum HFA

The maximum HFA, maximum passive pressure, standardized HFA, and VAS of maximum HFA of both groups are shown in Figure 4. Significant interactions were present between maximum HFA and maximum passive pressure (maximum HFA, $p < .001$; maximum passive pressure, $p < .001$). These variables showed significant main effects of massage (maximum HFA, $p < .001$; maximum passive pressure, $p < .001$). Additionally, after 6 and 12 weeks of intervention the maximum HFA and maximum passive pressure were significantly higher than prior to the intervention (maximum HFA prior to the intervention versus after 6 weeks of massage, $p < .001$, 95% CI 1.8 to 6.0°; maximum HFA prior to the intervention versus after 12 weeks of massage, $p < .001$, 95% CI 4.3 to 8.6°; maximum passive pressure prior to the intervention versus after 6 weeks of massage, $p < .001$, 95% CI 1.6 to 5.0 N, maximum passive pressure prior to the intervention versus after 12 weeks of massage, $p < .001$, 95% CI 3.0 to 6.0 N). After 12 weeks of massage, the maximum HFA and maximum passive pressure were significantly higher than after 6 weeks of massage (maximum HFA after 6 weeks versus after 12 weeks of massage, $p < .001$, 95% CI 1.2 to 4.0°; maximum passive pressure after 6 weeks versus after 12 weeks of massage, $p = .04$, 95% CI .03 to 2.4 N). Conversely, there were no significant main effects and no differences between the measurement times were found for these variables in the control group. There were no significant interactions between main effects or differences between measurement times in either group for the standardized HFA and the VAS of maximum HFA.

3.2. Stiffness of the muscle-tendon unit, the musculotendinous junction, and the muscle belly

The stiffnesses of the muscle-tendon unit, the musculotendinous junction, and the muscle belly in both groups are shown in Figure 5. No significant interactions between the main effects and the different measurement times were found in either group.

3.3. Pennation angle, muscle thickness and fascicle length of the semitendinosus muscle

The pennation angle, muscle thickness, and fascicle length of the semitendinosus muscle of both groups are shown in Table 2. There were no significant interactions between main effects and the different measurement times for any of these variables.

4. Discussion

Long-term self-massage at the musculotendinous junction increased the maximum HFA and the maximum passive pressure. Additionally, these effects were greater at 12 weeks than at 6 weeks. However, the VAS of the maximum HFA did not change over time. These results suggest that the massage intervention enabled participants to tolerate higher levels of pressure for the same amount of pain sensation. In contrast, massage did not influence the standardized HFA, the stiffness of the muscle-tendon unit, the musculotendinous junction, or the muscle belly, which suggests that long-term self-massage at the musculotendinous junction does not change the stiffness of the longitudinal or transverse axis of the hamstring. The structural indices of the hamstring also did not change during the study period.

In concordance with the results of other studies that examined the effects of SS on hamstring extensibility (Ben & Harvey, 2010; Folpp et al., 2006; Halbertsma & Göeken, 1994; Law et al., 2009; Magnusson et al., 1996), our results suggest that long-term self- massage at the musculotendinous junction increases hamstring extensibility by improving stretch tolerance. Laessoe and Voigt (2004) observed that the passive range of knee extension in a stooping position was less than in an upright position, and decreased with maximum dorsiflexion of the ankle. Therefore, they reasoned that changes in stretch tolerance could be attributed to stresses on the spinal and peripheral nerves, but not the joints. Based on their report, the physical stimulation of massage at the musculotendinous junction may affect neighboring neural pathways and decrease stress on the peripheral nerves, which may contribute to the improvement in stretch tolerance that we observed in this study.

Our current results indicate that long-term self-massage does not change hamstring stiffness. Considering that the decrease in spinal motor neuron excitability seen after massage lasts less than 1 minute after the intervention (Behm et al., 2013), our results may be attributed to the lack of change in the mechanical characteristics of the muscle-tendon unit and the muscle structure.

Our study had two limitations. First, we used a within-subject design in this study. This design has the advantage of minimizing between-group variability due to personal factors such as exercise and activity patterns (Ben & Harvey, 2010; Folpp et al., 2006; Law et al., 2009); however, a disadvantage of this study design is that the effects of massage may extend to the contralateral leg. However, the results of a recent study similar to ours (Ben & Harvey, 2010) suggest that stretching one leg does not affect the contralateral leg. Thus it seems likely that any effect of the massage on the contralateral leg in our study will be negligible. Second, we relied on self-reporting to assess compliance with the intervention.

Therapists, coaches, and athletes widely believe that massage is an effective means of increasing hamstring extensibility (Tiidus, 1997). In fact, previous studies have suggested that a single massage at the musculotendinous junction instantaneously increased hamstring extensibility (Akazawa et al., 2013; Huang et al., 2010). Also, the results of the current study suggest that long-term self-massage at the musculotendinous junction increases hamstring extensibility by improving stretch tolerance, although this intervention does not change hamstring stiffness.

5. *Conclusion*

The results of this study suggest that long-term self-massage at the musculotendinous junction increases hamstring extensibility by improving stretch tolerance. Then, this effect was greater after 12 weeks of massage than after 6 weeks. However, this intervention does not change hamstring stiffness and muscle structure.

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Conflict of interest statement

The authors have no conflicts of interest to declare.

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References

Akagi, R., & Takahashi, H. (2014). Effect of a 5-week static stretching program on hardness of the gastrocnemius muscle. *Scandinavian Journal of Medicine & Science in Sports*, 24, 950-957.

Akazawa, N., Harada, K., Okawa, N., Oka, T., Nakatani, K., Yamanaka, R., Nishikawa, K., Tamura, K., Kitaura, M., & Matsui, Y. (2013). Effects of massage at two difference hamstring positions on hip flexion angle in healthy males. *Journal of The Japanese Physical Therapy Association*, 40, 71-78. [in Japanese with English abstract].

Bandy, W. D., Irion, J. M., & Briggler, M. (1997). The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Physical Therapy*, 77, 1090-1096.

Barlow, A., Clarke, R., Johnson, N., Seabourne, B., Thomas, D., & Gal, J. (2004). Effect of massage of the hamstring muscle group on performance of the sit and reach test. *British Journal of Sports Medicine*, 38, 349-351.

Behm, D. G., Peach, A., Maddigan, M., Aboodarda, S. J., DiSanto, M. C., Button, D. C., & Maffiuletti, N. A. (2013). Massage and stretching reduce spinal reflex excitability without affecting twitch contractile properties. *Journal of*

Electromyography and Kinesiology, 23, 1215-1221.

Ben, M., & Harvey, L. A. (2010). Regular stretch does not increase muscle extensibility: a randomized controlled trial. *Scandinavian Journal of Medicine & Science in Sports*, 20, 36-144.

Bijur, P. E., Silver, W., & Gallagher, E. J. (2001). Reliability of the visual analog scale for measurement of acute pain. *Academic Emergency Medicine*, 8, 1153-1157.

Bradley, P. S., & Portas, M. D. (2007). The relationship between preseason range of motion and muscle strain injury in elite soccer player. *Journal of Strength and Conditioning Research*, 21, 1155-1159.

Folpp, H., Deall, S., Harvey, L. A., & Gwinn, T. (2006). Can apparent increases in muscle extensibility with regular stretch be explained by changes in tolerance to stretch?. *Australian Journal of Physiotherapy*, 52, 45-50.

Gauvin, M. G., Riddle, D. L., & Rothstein, J. M. (1990). Reliability of clinical measurements of forward bending using the modified fingertip-to-floor method. *Physical Therapy*, 70, 443-447.

Goldberg, J., Sullivan, S. J, & Seaborne, D. E. (1992). The effect of two intensities of massage on H-reflex amplitude. *Physical Therapy*, 72, 449-457.

Goldberg, J., Seaborne, D. E., Sullivan, S. J., & Leduc, B. E. (1994). The effect of therapeutic massage on H-reflex amplitude in persons with a spinal cord injury. *Physical Therapy*, 74, 728-737.

Halbertsma, J. P., & Göeken, L. N. (1994). Stretching exercise: effect on passive extensibility and stiffness in short hamstrings of healthy subjects. *Archives of Physical Medicine and Rehabilitation*, 75, 976-981.

Hopper, D., Conneely, M., Chromiak, F., Canini, E., Berggren, J., & Briffa, K. (2005a). Evaluation of the effect of two massage techniques on hamstring muscle length in competitive female hockey players. *Physical Therapy in Sport*, 6, 137-145.

Hopper, D., Deacon, S., Das, S., Jain, A., Riddell, D., Hall, T., & Briffa, K. (2005b). Dynamic soft tissue mobilization increases hamstring flexibility in healthy male subjects. *British Journal of Sports Medicine*, 39, 594-598.

Huang, S. Y., Di, Santo, M., Wadden, K. P., Cappa, D. F., Alkanani, T., & Behm, D. G. (2010). Short-duration massage at the hamstrings musculotendinous junction induces greater range of motion. *Journal of Strength and Conditioning Research*, 24, 1917-1924.

Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *Journal of Applied Physiology*, 88, 811-816.

Laessoe, U., & Voigt, M. (2004). Modification of stretch tolerance in a stooping position. *Scandinavian Journal of Medicine & Science in Sports*, 14, 239-244.

Law, R. Y., Harvey, L.A., Nicholas, M.K., Tonkin, L., De, Sousa, M., & Finniss, D. G. (2009). Stretch exercises increase tolerance to stretch in patients with chronic musculoskeletal pain: a randomized controlled trial. *Physical Therapy*, 89: 1016-1026, 2009.

Magnusson, S. P., Simonsen, E. B., Aagaard, P., Sørensen, H., & Kjaer, M. (1996). A mechanism for altered flexibility in human skeletal muscle. *Journal of Physiology*, 497, 291-298.

Marshall, P. W., Mannion, J., & Murphy, B. A. (2009). Extensibility of the hamstrings is best explained by mechanical components of muscle contraction, not behavioral measures in individuals with chronic low back pain. *PM&R*, 1, 709-718.

Marshall, P. W., 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. *Journal of Science and Medicine in Sport*, 14, 535-540.

McHugh, M. P., Kremenic, I. J., Fox, M. B., & Gleim, G. W. (1998). The role of mechanical and restraints to joint range of motion during passive stretch.

Medicine & Science in Sports & Exercise, 30, 928-932.

McHugh, M. P., Connolly, D. A., Eston, R. G., Kremenic, I. J., Nicholas, S. J., & Gleim, G.W. (1999). The role of passive muscle stiffness in symptoms of exercise-induced muscle damage. *American Journal of Sports Medicine*, 27, 594-599.

Morse, C. I., Degens, H., Seynnes, O. R., Maganaris, C. N., & Jones, D. A. (2008). The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. *Journal of Physiology*, 586, 97-106.

Murayama, M., Nosaka, K., Yoneda, T., & Minamitani, K. (2000). Changes in hardness of the human elbow flexor muscles after eccentric exercise. *European Journal of Applied Physiology*, 82, 361-367.

Nakamura, M., Ikezoe, T., Takeno, Y., & Ichihashi, N. (2012). Effects of a 4-week static stretch training program on passive stiffness of human gastrocnemius muscle-tendon unit in vivo. *European Journal of Applied Physiology*, 112, 2749-2755.

Samukawa, M., Hattori, M., Sugama, N., & Takeda, N. (2011). The effects of dynamic stretching on planter flexor muscle-tendon tissue properties. *Manual Therapy*, 16, 618-622.

Tiidus, P. (1997). Manual massage and recovery of muscle function following exercise: a literature review. *Journal of Orthopaedic and Sports Physical Therapy*, 25, 107-112.

Weppler, C. H., & Magnusson, S. P. (2010). Increasing muscle extensibility: a matter of increasing length or extensibility?. *Physical Therapy*, 90, 438-449.

Wiktorsson-Möller, M., Oberg, B., Ekstrand, J., & Gillquist, J. (1983). Effects of warming up, massage and stretching on range of motion and muscle strength in the lower extremity. *American Journal of Sports Medicine*, 11, 249-252.

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. *American Journal of Sports Medicine*, 31, 41-46.

Ylinen, J., Kankainen, T., Kautiainen, H., Rezasoltani, A., Kuukkanen, T., & Hakkinen, A. (2009). Effect of stretching on hamstring muscle compliance. *Journal of Rehabilitation Medicine*, 41, 80-84.

Table 1. Characteristics of the participants (n = 37)

Age (year)	27.1 ± 6.8
Height (cm)	173.1 ± 6.1
Weight (kg)*	71.6 ± 16.1
Skeletal muscle mass（kg）*	31.7 ± 4.4
Fat mass（kg）*	15.3 ± 10.5

Values are presented as mean ± standard deviation.

*Weight, skeletal muscle mass, and fat mass were measured by bioelectrical impedance analysis.

Table 2. Changes in the pennation angle, the muscle thickness, and the muscle fascicle length of the semitendinosus

	Massage group				Control group				Interaction effect[b]
	pre	6 weeks	12 weeks	main effect[a]	pre	6 weeks	12 weeks	main effect[a]	
Pennation angle (Degree)	7.0 ± 1.6	7.1 ± 1.6	7.0 ± 1.5	p = 0.75	6.8 ± 1.5	6.9 ± 1.5	6.9 ± 1.5	p = 0.73	p = 0.86
Muscle thickness (cm)	2.2 ± 0.2	2.2 ± 0.2	2.2 ± 0.2	p = 0.86	2.2 ± 0.2	2.2 ± 0.2	2.2 ± 0.3	p = 0.94	p = 0.84
Muscle fascicle length (cm)	20.2 ± 4.9	19.7 ± 4.4	19.5 ± 4.4	p = 0.19	20.3 ± 4.9	20.5 ± 5.5	19.6 ± 3.7	p = 0.16	p = 0.99

[a] Repeated measure analysis of variance (Test time)

[b] Two way analysis of variance (Experimental group × Test time)

Figure captions

Figure 1. Technique for self-massage at the musculotendinous junction.

Figure 2. Measurement of the hip flexion angle.

Figure 3. The ultrasound image obtained from the semitendinosus muscle at a 50 degree hip flexion angle. "θ" represents the pennation angle of semitendinosus. "A" represents the muscle thickness of semitendinosus.

Figure 4. Changes in the maximum HFA, the maximum passive pressure, the standardized HFA, and the VAS of maximum HFA. *Significant difference between pre-intervention and after 6 or 12 weeks of intervention, $p < .001$. †Significant difference between after 6 and after 12 weeks of intervention, $p < .001$. ‡Significant difference between after 6 and after 12 weeks of intervention, $p = .04$. Circle and solid line = massage group, triangle and dashed line = control group, and pre = prior to intervention.

Figure 5. Changes in the stiffness of the muscle-tendon unit, the musculotendinous junction, and the muscle belly. Circle and solid line = massage group, triangle and dashed line = control group, and pre = prior to intervention.

Figure 1

Figure 2

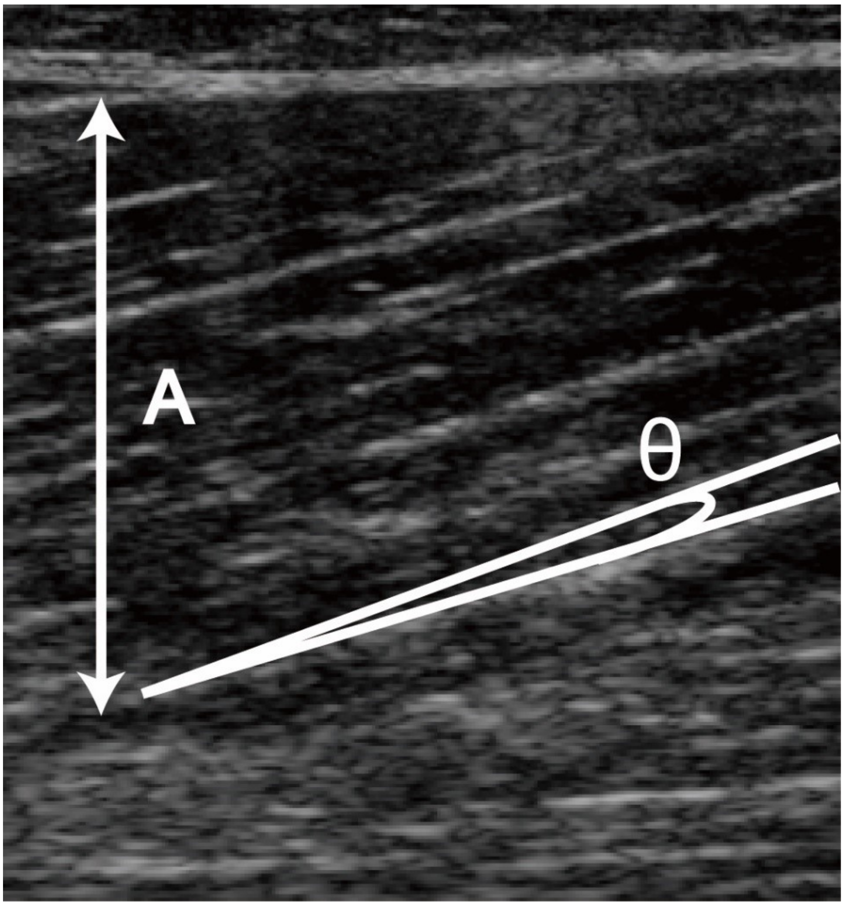

Figure 3

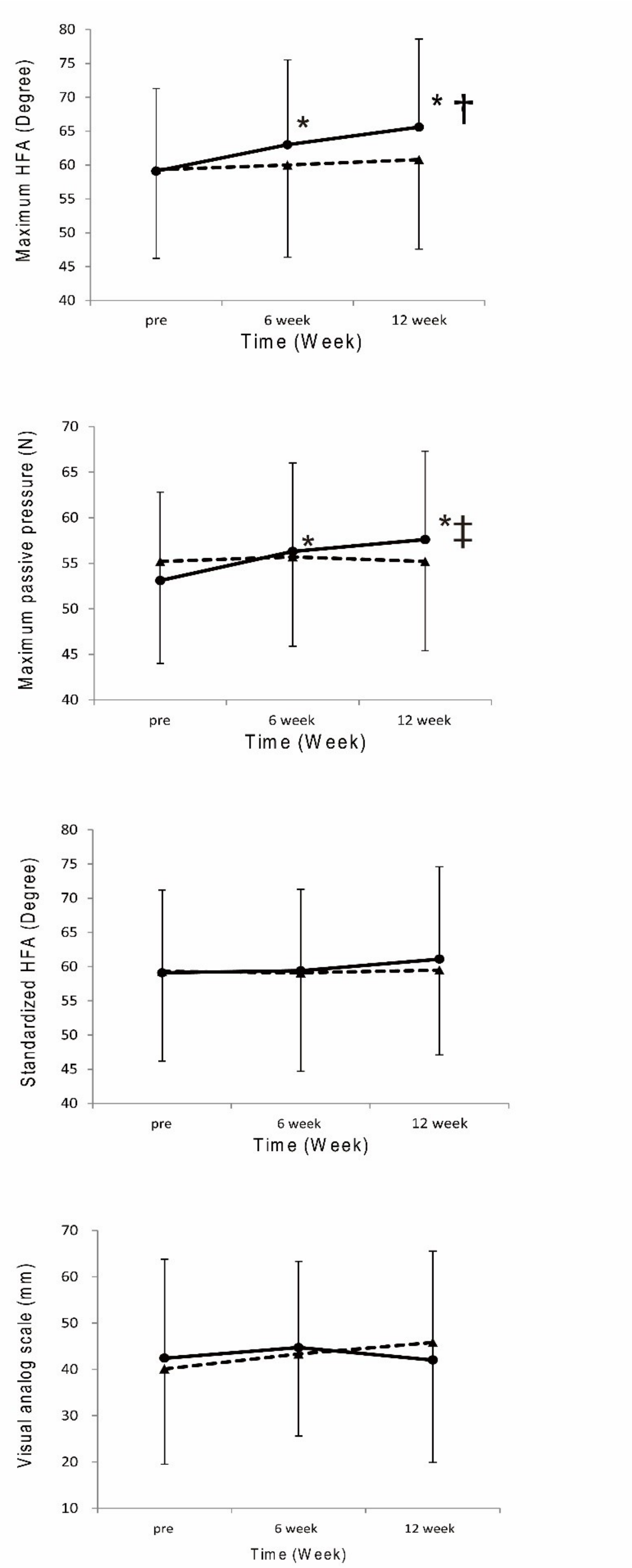
80
75
70
65
60
55
50
45
40
Maximum HFA (Degree)
pre
6 week
12 week
Time (Week)
*
* †
70
65
60
55
50
45
40
Maximum passive pressure (N)
pre
6 week
12 week
Time (Week)
*
*‡
80
75
70
65
60
55
50
45
40
Standardized HFA (Degree)
pre
6 week
12 week
Time (Week)
70
60
50
40
30
20
10
Visual analog scale (mm)
pre
6 week
12 week
Time (Week)

Figure 4

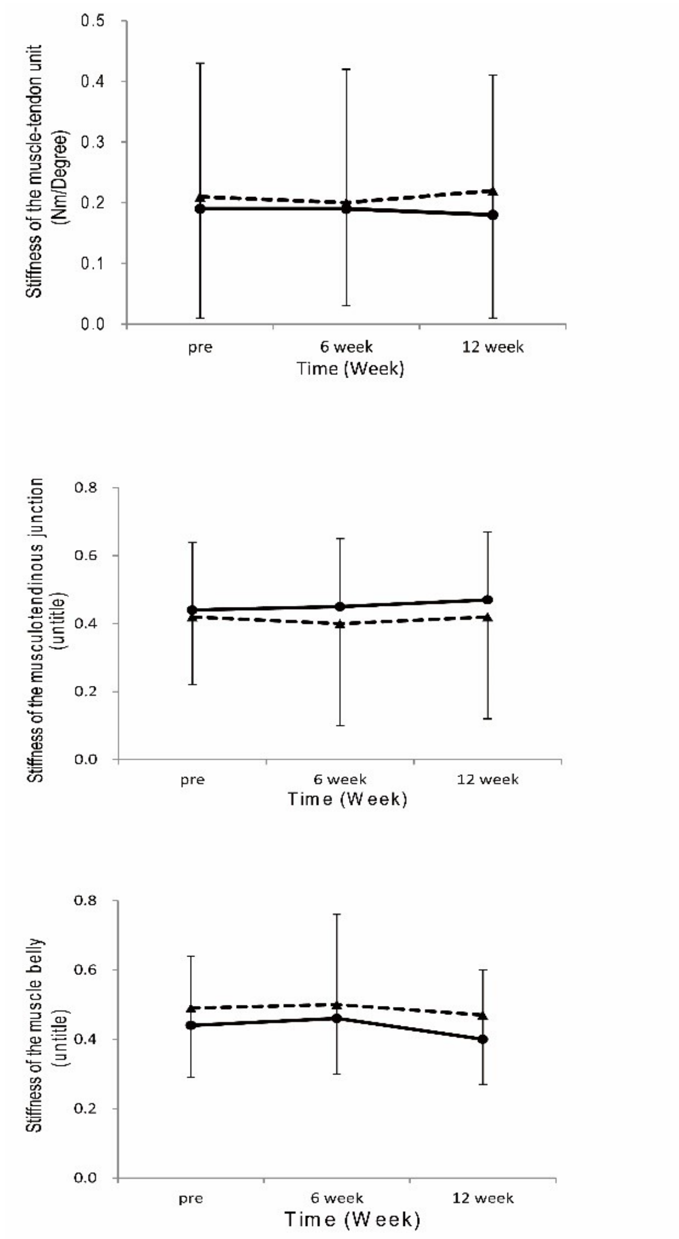
0.5
0.4
0.3
0.2
0.1
0.0
Stiffness of the muscle-tendon unit
(Nm/Degree)
pre
6 week
12 week
Time (Week)
0.8
0.6
0.4
0.2
0.0
Stiffness of the musculotendinous junction
(untitle)
pre
6 week
12 week
Time (Week)
0.8
0.6
0.4
0.2
0.0
Stiffness of the muscle belly
(untitle)
pre
6 week
12 week
Time (Week)

Figure 5