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ORIGINAL ARTICLE

Influence of stress relaxation and load during static stretching on the range of motion and muscle–tendon passive stiffness

Taizan Fukaya[1,2] · Masatoshi Nakamura[1,3] · Shigeru Sato[1,3] · Ryosuke Kiyono[1,3] · Kaoru Yahata[1,3] · Kazuki Inaba[3] · Satoru Nishishita[4,5,6] · Hideaki Onishi[1,3]

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Abstract

Purpose Passive torque during static stretching was decreased. This phenomenon occurs due to stress relaxation. However, no studies have investigated the relationship stress relaxation and changes in range of motion (ROM) or muscle–tendon unit stiffness. Moreover, no study calculated the total volume during static stretching as total work and investigated the relationship between total work and ROM changes or muscle–tendon stiffness. This study aimed to investigate the relationship between stress relaxation, total work from measuring passive torque normalized by muscle thickness and ROM, and muscle–tendon stiffness.

Methods A total of 63 healthy students voluntarily participated in this study. Static stretching was performed for the plantar flexor muscles at 120 s. Outcomes were assessed on ROM, passive torque at dorsiflexion ROM, and muscle–tendon stiffness. Stress relaxation was defined as the change of torque from the start to end of static stretching. Total work was defined as the sum of the torque from the start to end of static stretching.

Results Stress relaxation was found to be significantly correlated with muscle–tendon stiffness whether normalized by muscle thickness or not ($r = 0.603$, $r = 0.599$). Furthermore, total work was significantly correlated with muscle–tendon stiffness, regardless of normalization ($r = -0.276$, $r = -0.327$). However, the relationship among stress relaxation, total work and ROM, and passive torque at dorsiflexion ROM was not significant.

Conclusion Stress relaxation and total work are associated with muscle–tendon stiffness changes after stretching, but not associated with ROM changes.

Keywords Static stretching · Stress relaxation · Total work · Muscle–tendon stiffness

✉ Taizan Fukaya
hwd19012@nuhw.ac.jp

1 Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, 1398 Shimami-cho, Kita-ku, Niigata, Niigata 950-3198, Japan

2 Department of Rehabilitation, Kyoto Kujo Hospital, 10 Karahashirajoumoncho, Minami-ku, Kyoto 601-8453, Japan

3 Department of Physical Therapy, Niigata University of Health and Welfare, 1398 Shimami-cho, Kita-ku, Niigata, Niigata 950-3198, Japan

4 Graduate School of Medicine, Kyoto University, 53 Kawara-cho, Shogoin, Sakyo-ku, Kyoto 606-8507, Japan

5 Institute of Rehabilitation Science, Tokuyukai Medical Corporation, 3-11-1 Sakuranocho, Toyonaka, Osaka 560-0054, Japan

6 Kansai Rehabilitation Hospital, Tokuyukai Medical Corporation, 3-11-1 Sakuranocho, Toyonaka, Osaka 560-0054, Japan

Abbreviations

CI	Confidence interval
LG	Lateral gastrocnemius muscle
MG	Medial gastrocnemius muscle
MTU	Muscle–tendon unit
SOL	Soleus muscle
SR	Stress relaxation
SS	Static stretching
ROM	Range of motion

Introduction

Stretching is commonly performed in several fields, such as sports and rehabilitation settings. Generally, static stretching (SS) is one of various stretching methods and performed to stretch the muscle and maintain the length position of the muscle for several seconds [1]. It is mainly performed to improve flexibility, and several previous studies reported the range of motion (ROM) was used as flexibility index and increased after SS [2, 3]. Moreover, a previous study [2] reported that ROM increment mechanisms were changing in accordance with the sensation to tolerate loading before terminating the stretch (i.e., increased stretch tolerance) [4, 5] and with the viscoelastic properties of the muscle–tendon unit (MTU) (i.e., decrease of MTU stiffness) [6, 7]. Previous studies investigating the effects of SS on these outcomes showed that longer duration [8] or high intensity [9] more effectively changes ROM and MTU stiffness.

Previous studies reported that passive torque during SS, measured using an isokinetic dynamometer, was decreased from the onset to end of stretching [8, 10]. This phenomenon occurs due to stress relaxation (SR), which reduces the passive torque when MTU is stretched and held at a constant length [10, 11]. Purslow et al. reported that the greater SR in perimysium was shown at the higher elongation in vivo [12]. Furthermore, Kataura et al. reported that stretching intensity was moderately positively correlated with the relative ROM or passive stiffness change [9]. As described above, SR by SS is possibly associated with changes in ROM and/or MTU stiffness. However, to the best of our knowledge, no studies have investigated the relationship between SR and ROM changes or MTU stiffness.

Recently, studies of investigation of the effects of resistance training have focused on total work calculated from load, times, and number of sets during training [13, 14]. Their results suggested that total work given to the muscle was important for resistance training rather than only training load, times, and number of sets. Although total work for muscle during stretching can be assumed to be an important factor for inducing changes in ROM or passive stiffness after stretching intervention, no study has yet calculated the total volume from passive torque during stretching as the total work. Cabido et al. reported that constant-torque stretching, which maintains the passive torque during stretching promoted greater changes in ROM and passive stiffness than constant-angle stretching, which maintains the same angle during stretching [15]. These results suggested that greater passive torque applied to the muscle (e.g., total volume during constant-torque stretching) could induce greater changes in ROM and passive stiffness rather than constant-angle stretching. Therefore, measuring total work of passive torque during SS and investigating the relationship between total work and change in ROM or MTU stiffness remain important. However, no study has investigated the relationship between changes in ROM or passive stiffness and total work or stress relaxation in a large number of participants.

Interestingly, Neto et al. reported that declined passive torque during stretching was significantly correlated with the passive torque at maximal ROM, thigh perimeter, thigh bone mass, thigh skeletal muscle mass, and body mass index [16]. Therefore, the amount of SR and total work measured by passive torque might be influenced by volume of muscle thickness or thigh perimeter. Therefore, the passive torque during stretching with thigh perimeter and muscle thickness should be normalized to investigate the relationship among SR, total work, and ROM changes or muscle–tendon stiffness. However, to the best of our knowledge, no study investigated the relationship between SR and total work using a normalized passive torque and ROM changes or MTU stiffness. Thus, the study aimed to investigate the relationship between SR and total work from measuring passive torque normalized by muscle thickness and ROM changes or MTU stiffness. Previous studies reported that SR was positively correlated with thigh skeletal muscle mass and body weight [16]. Further, Kataura et al. reported that higher-intensity stretching was shown to be greater ROM change, passive stiffness, and amount of SR in the same subjects [9]. Therefore, it was hypothesized that SR or total work was positively correlated with ROM changes or muscle–tendon stiffness among different participants.

Methods

Participants

A total of 63 healthy university students (males, 36 students; females, 27 students) voluntarily participated in this study (age, 21.0 ± 0.2 years; height, 166.6 ± 8.5 cm; body mass, 59.7 ± 10.1 kg). All participants were excluded if they had history of an operation performed on their back or lower extremity, lower-extremity contracture, neurological disorders, and took hormone or muscle affecting drugs. Written informed consent was obtained from all participants. In addition, this study was approved by the ethics committee of our institution.

Study design and overview

A pre- and post-stretching evaluation was conducted in this study. Participants performed 120-s SS at the plantar flexor muscles. First, muscle thickness of the plantar flexor muscle was measured before SS. Then, dorsiflexion ROM and passive torque at dorsiflexion ROM [4] were measured before (PRE) and after (POST) SS. Additionally, passive torque during SS was measured, and was used for calculating SR [10] and total work.

Procedures

Measurement of range of motion, passive torque at dorsiflexion range of motion, and muscle–tendon unit stiffness

Participants were seated in the isokinetic dynamometer (Biodex system 3.0; Shirley, NY, USA) chair at 0° knee angle (i.e., the anatomical position) and 70° hip flexion to prevent tension at the back of the knee, with adjustable belts over the trunk and pelvis and the ankle was fixed to the footplate [17]. Then, participants moved the footplate of the dynamometer starting from the ankle 0° angle to the maximum dorsiflexion angle without feeling pain at 5°/s speed to measure the torque–angle curve [6].

ROM, passive torque at dorsiflexion ROM, and MTU stiffness were measured by calculating the torque–angle curve from the ankle 0° angle to the maximum dorsiflexion angle without feeling pain using a isokinetic dynamometer [8]. ROM (°) was defined as the maximum dorsiflexion angle. Passive torque at dorsiflexion ROM (Nm) defined passive torque as the point of maximum dorsiflexion [17]. MTU stiffness (Nm/°) was defined as the slope of the regression line between 50 and 100% torque–angle relationship when the minimum ROM was recorded [8] (Fig. 1).

Muscle thickness measurement

B mode ultrasonography (LOGIQ e V2; GE Healthcare Japan, Tokyo, Japan) using an 8 MHz linear probe was used to determine the muscle thickness of plantar flexor muscles. Participants were instructed to lay down on a bed in the prone position. The muscle thickness of medial gastrocnemius muscle (MG) or lateral gastrocnemius muscle (LG) was measured at 30% level and soleus muscle (SOL) at 50% level of the lower leg length [18]. Then, the sum of the thickness of the three muscles (MG, LG, and SOL) was adopted as representative of the size of the plantar flexor muscles [18].

Measurement of stress relaxation and total work during stretching (Fig. 2)

SR was defined as the passive torque change from the onset to the end of stretching [8, 19]. The total work was defined as the sum of the passive torque during SS from the onset to the end of stretching. Additionally, SR and total work were normalized to muscle thickness.

Static stretching

SS was performed for the plantar flexor muscles in a similar position with the measurement. Participants moved the footplate of the dynamometer from the ankle at 0° angle to the maximum dorsiflexion angle without feeling pain [3] at 5°/s speed and held on 120 s at the angle.

Measurement reliability

The test–retest reliabilities for ROM, passive torque at dorsiflexion ROM, and muscle–tendon stiffness were determined before the present study using two tests performed in eight healthy students. The calculated intraclass coefficients for ROM, passive torque at dorsiflexion, and muscle–tendon stiffness were 0.95 [95% confidence interval (CI) 0.81–0.99], 0.90 (95% CI 0.63–0.98), and 0.93 (95% CI 0.73–0.99), respectively, indicating that the reliability high for all outcome measures [20].

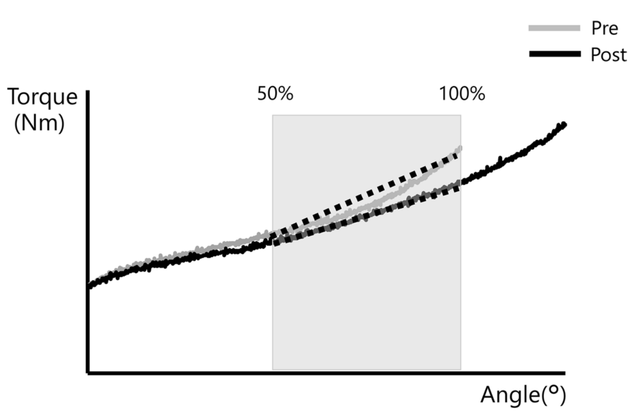

Fig. 1 Typical torque–angle curves of a patient at pre- and post-stretching. Muscle–tendon stiffness (broken line) was determined by a regression line between 50 and 100% torque–angle relationship when the minimum ROM was recorded

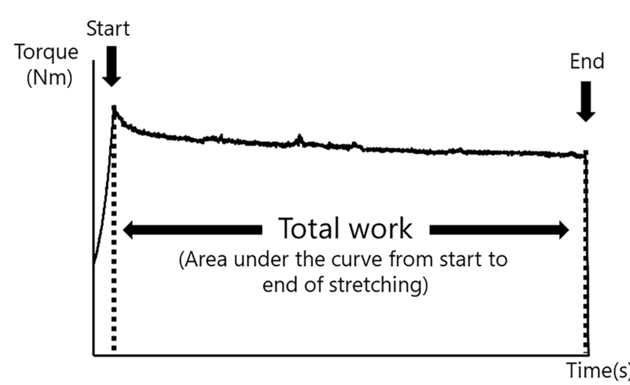

Fig. 2 Passive torque changes during static stretching. Stress relaxation was determined as the difference of passive torque from the start to end of stretching. Total work was determined as the sum of the passive torque from the start to end of stretching

Statistical analysis

Normality of the data was assessed by a Shapiro–Wilk test. This test showed that ROM, passive torque at dorsiflexion ROM, and MTU stiffness were not disturbed. Therefore, Wilcoxon signed-rank test was performed to compare the differences between pre- and post-stretching for ROM, passive torque at dorsiflexion ROM, and MTU stiffness. Spearman's rank order correlation analysis was used to determine the relationship between passive torque at dorsiflexion during pre-stretching and MTU stiffness or muscle thickness. In addition, Spearman's rank order correlation analysis was used to determine the relationship between ROM changes, passive torque at dorsiflexion ROM, and MTU stiffness and SR or total work. Moreover, to clarify the mechanism of ROM increase, Spearman's rank order correlation analysis was used to determine the relationship between ROM changes and passive torque at dorsiflexion ROM or MTU stiffness. All statistical analyses were performed using R2.8.1 (CRAN, freeware), $p < 0.05$ indicating statistical significance. All data are presented as mean ± standard deviation.

Results

Effects of static stretching on range of motion, passive torque at dorsiflexion range of motion, and muscle–tendon unit stiffness

ROM significantly increased after SS (PRE: 26.4 ± 9.5°, POST: 29.5 ± 9.5°, $p < 0.01$). Whereas, there were no significant change in passive torque at dorsiflexion ROM (PRE: 37.0 ± 14.4 Nm, POST: 37.7 ± 14.4 Nm, $p = 0.11$). MTU stiffness decreased significantly from pre- to post-stretching (PRE: 1.1 ± 0.6 Nm/°, POST: 0.9 ± 0.5 Nm/°, $p < 0.01$). In addition, Spearman's rank order correlation analysis indicated a positive correlation between ROM changes and passive torque at dorsiflexion ROM ($\rho = 0.77$, $p < 0.01$). However, no significant correlation coefficients were observed between ROM changes and muscle–tendon stiffness ($\rho = -0.21$, $p = 0.09$).

Relationship between passive torque, muscle–tendon stiffness, and muscle thickness

Muscle thickness of each plantar flexor muscles was shown (MG, 1.8 ± 0.2 cm; LG, 1.6 ± 0.3 cm; SOL, 1.7 ± 0.3 cm), and the sum of muscle thickness in three muscles was 5.1 ± 0.7 cm. Spearman's rank order correlation analysis indicated passive torque at dorsiflexion ROM at PRE was significantly positively correlated with muscle thickness ($\rho = 0.30$, $p = 0.02$). In addition, Spearman's rank order correlation analysis indicated a positive correlation between MTU stiffness at PRE and muscle thickness ($\rho = 0.27$, $p = 0.03$).

Relationship between range of motion, passive torque at dorsiflexion range of motion, muscle–tendon unit stiffness and stress relaxation, and total work

The relationship between ROM changes, passive torque at dorsiflexion ROM, and MTU stiffness and SR, and total work is shown in Table 1. Higher positive correlation was found between MTU stiffness changes and SR ($\rho = 0.40$, $p < 0.01$). However, ROM changes ($\rho = -0.076$, $p = 0.56$) were not significantly correlated with passive torque at dorsiflexion ROM ($\rho = 0.04$, $p = 0.76$) and SR. As shown in Table 1, these results were the same regardless of normalizing the passive torque by muscle thickness (ROM: $\rho = -0.035$, $p = 0.78$; passive torque at dorsiflexion ROM: $\rho = 0.10$, $p = 0.42$; muscle–tendon stiffness; $\rho = 0.41$, $p < 0.01$). Similarly, Spearman's rank order correlation analysis indicated a lower negative correlation between the MTU stiffness change and total

Table 1 Correlation coefficients between the change in ROM, passive torque at dorsiflexion ROM, and muscle–tendon stiffness and stress relaxation, total work

	ROM changes (°)	Passive torque at DF ROM changes (Nm)	Muscle–tendon stiffness changes (Nm/°)
Stress relaxation (Nm)	$\rho = -0.076$ $p = 0.56$	$\rho = 0.040$ $p = 0.76$	$\rho = 0.40$ $p < 0.01$
Stress relaxation/muscle thickness (Nm/cm)	$\rho = -0.035$ $p = 0.78$	$\rho = 0.10$ $p = 0.42$	$\rho = 0.41$ $p < 0.01$
Total work (Nm)	$\rho = 0.00050$ $p = 1.0$	$\rho = 0.11$ $p = 0.39$	$\rho = -0.27$ $p = 0.035$
Total work/muscle thickness (Nm/cm)	$\rho = -0.042$ $p = 0.74$	$\rho = 0.054$ $p = 0.68$	$\rho = -0.29$ $p = 0.020$

ROM range of motion, *DF* dorsiflexion work ($\rho = -0.27$, $p = 0.03$). However, no significant correlations were observed between ROM changes ($\rho = 0.00050$, $p = 0.997$), passive torque at dorsiflexion ROM ($\rho = 0.11$, $p = 0.39$), and total work regardless of normalization (ROM: $\rho = -0.042$, $p = 0.74$; passive torque at dorsiflexion ROM: $\rho = 0.053$, $p = 0.68$).

Discussion

The present study investigated the relationship between SR and total work from measuring passive torque normalized by muscle thickness and ROM changes or MTU stiffness after a 120-s SS. Results showed a significant correlation between SR or total work and MTU stiffness changes, regardless of normalized by muscle thickness. Conversely, SR or total work was not significantly correlated with ROM changes and passive torque at dorsiflexion ROM, regardless of normalization.

This study showed that ROM significantly increased after a 120-s SS. Generally, the mechanism of increased ROM might be involved by changing the stretch tolerance [4, 5] and decreasing the MTU stiffness [6, 7].This study showed that ROM significantly increased and muscle–tendon stiffness decreased significantly after a 120-s SS, and these results were similar to that of a previous study [21]. Nakamura et al. reported that the decreasing MTU stiffness was required > 120 s [21], which was consistent with our results. However, no significant correlation was observed between the dorsiflexion ROM change and MTU stiffness, and our results suggested that increased dorsiflexion ROM might not be influenced with change in viscoelasticity MTU. Kay et al. reported that significant positive correlation was observed between increased ROM and passive torque change at dorsiflexion ROM, and concluded that increased ROM contributed to increased stretch tolerance [22]. Similar to a previous study, this study found that ROM changes were significantly positively correlated with passive torque at dorsiflexion ROM ($\rho = 0.77$, $p < 0.01$), and these results showed that increased ROM might be caused by increasing stretch tolerance.

Interestingly, our study found that decreased passive torque during SS (SR) was significantly positively correlated with MTU stiffness change. Decreased passive torque during stretching resulted from SR, which is declining passive torque when the muscle is stretched and held at a constant angle [10, 11]. Sobolewski et al. suggested that SR during SS was primarily a viscous response [19]. Previous studies reported that SR was correlated to MTU junction displacement [21] or fascicle length changes [23]. Therefore, with greater SR changes caused by higher elongation of MTU properties, changes in viscoelastic properties of MTU may be larger, that is, decreased MTU stiffness. Conversely, ROM or passive torque changes at dorsiflexion ROM were not significantly correlated with SR in this study. As mentioned above, ROM and passive torque at dorsiflexion ROM resulted in stretch tolerance, and a previous study suggested that stretch tolerance was related with neural and psychological factor changes [24]. Thus, SR may be associated with viscoelastic property changes of MTU, not neural and psychological factors. In addition, because increased ROM was influenced not only by MTU stiffness changes but also by stretch tolerance changes in this study, ROM changes may not be correlated with SR.

We found that SR was significantly positively correlated with muscle thickness of the plantar flexor muscles, which was consistent with that of the previous study [16]. Therefore, SR was assumed to normalize the physical characteristics to investigate the effects of stretching among individuals. As a result, SR normalized by muscle thickness of the plantar flexor muscle was significantly negatively correlated to MTU stiffness changes; however, the magnitude of correlation was similar to the result that was not normalized. Therefore, SR may be associated with decreased MTU stiffness, regardless of each subjects' muscle thickness of the plantar flexor muscles.

To the best of our knowledge, no study has calculated the total work using passive torque to investigate the effects of stretching. Contrary to our hypothesis, total works were significantly negatively correlated to MTU stiffness changes, but not to ROM or passive torque changes at dorsiflexion ROM. These results showed that the total work might not be associated with the effects of stretching on ROM and stretch tolerance, but slightly associated with decreased MTU stiffness. A previous study reported that ROM and MTU stiffness changes after a constant-torque stretching were greater than that after a constant-angle stretching [15]. These results suggested that the total work of constant-torque stretching was greater than that of constant-angle stretching because of decreased passive torque during a constant-angle stretching, but maintained during a constant-torque stretching. The MTU stiffness changes in this study were consistent with that of a previous study [15], suggesting that greater total work resulted in greater MTU stiffness changes among each subject; however, Spearman's rank order correlation analysis indicated a lower negative correlation ($\rho = -0.27$). The discrepancy between the previous study and our results might be influenced by the subjects' characteristics. The previous study investigated the effect of different total works on MTU stiffness between the same subjects [15], whereas effects of different total works on MTU stiffness were investigated among different subjects in this study. Therefore, the total work might not affect the effect of stretching on MTU stiffness when comparing different subjects. In addition, Ryan et al. reported that MTU stiffness was significantly positively correlated with the muscle cross-sectional area of plantar flexor muscles ($r=0.83$) [25]. In this study, the MTU stiffness was significantly positively correlated with the muscle thickness of plantar flexor muscles ($\rho=0.27$); however, Spearman's rank order correlation analysis was lower than that of the previous study. Therefore, muscle thickness of plantar flexor muscles may not normalize the total work optimally. Therefore, future studies are needed to measure the muscle cross-sectional area using dual-energy X-ray absorptiometry and normalize the total work by cross-sectional area to compare the effects of stretching among different subjects.

This study had several limitations. First, the stretching intensity was defined based on an individual's sensation without feeling pain. Therefore, stretch tolerance might be different among subjects, and this difference might affect ROM and MTU stiffness changes. Freitas et al. reported that verbal and numerical scales were effectively used to investigate the stretching intensity [26]; thus, these tools should be used in the future study. Second, healthy university students were recruited for this study. Giuliani et al. reported that muscle cross-sectional area was not significantly different between young and elderly people; however, ROM and passive torque at dorsiflexion of young people was higher than that of elderly people [27]. Furthermore, Sobolewski et al. reported that SR changes in young people were greater than that in elderly people [28]. Therefore, SR and total work of elderly people should be investigated in future studies.

Conclusion

This study investigated the relationship between SR or total work normalized by muscle thickness and ROM and MTU stiffness changes after a 120-s SS. The results showed that SR or total work was significantly correlated with MTU stiffness changes, regardless of muscle thickness normalization, and these results suggested that SR and total work was associated with viscoelastic property changes of MTU. Conversely, our results showed that SR or total work might not be associated with ROM changes and stretch tolerance.

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

Declarations

Conflict of interest All the authors declare that there are no potential conflicts 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. This study was approved by the ethics committee of our institution.

Consent to participate Informed consent was obtained from all participants included in the study.

Consent for publication Consent for publication was obtained from all participants included in the study.

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