Title

Influence of constant torque stretching at different stretching intensities on flexibility and mechanical properties of plantar flexors.

ABSTRACT

The purpose of this study was to examine the effects of constant torque stretching (CTS) at different stretching intensities on the maximal range of motion (ROM) and muscle-tendon unit (MTU) stiffness of plantar flexors. Fourteen healthy men performed four trials of differing stretch intensity: no stretching (control), 50 %, 75 %, and 100 %. Stretch intensity was defined as maximum passive resistive torque predetermined at a familiarization trial. Each stretch trial consisted of five sets of 60-second CTS at the designated stretch intensity. Both maximal ROM and passive resistive torque were assessed during passive dorsiflexion and MTU stiffness was calculated using the torque-angle curves measured before and after CTS. There were no significant differences in maximal ROM or MTU stiffness at the baseline condition. After the intervention, significantly greater maximal ROM and significantly lower MTU stiffness were observed in the 100 % CTS condition than the control condition while there were no significant differences between the submaximal intensity condition (i.e. 50 % or 75 % intensity) and the control condition. Therefore, our findings suggest that maximal intensity stretching is the most effective approach for improving both flexibility and MTU stiffness with CTS.

Keywords

Constant torque stretching, stretching intensity, flexibility

INTRODUCTION

Stretching exercises are widely used to improve flexibility in the sports and rehabilitation fields. Numerous studies showed that stretching exercises induced acute increases in range of motion (ROM) (1-3) and changes in the stiffness of the muscle-tendon unit (MTU) (1, 4-7). Stretching exercises also enhance athletic performance (8, 9) and reduce the risks of sports-related injury (10).

Stretching intensity, duration, frequency, position and technique are all important factors that can influence stretch-induced effects (11, 12). Much research has been conducted in attempt to clarify and establish effective static stretching protocols. Constant angle stretching (CAS) is a stretching technique defined by holding a muscle group at a constant length to maintain a specific joint angle, while Constant Torque Stretching (CTS) is defined by holding passive resistive torque to adjust joint angles. Recent studies have shown that CTS is more effective than CAS for increasing ROM (12, 13) and decreasing MTU stiffness; one of the mechanical properties of the MTU (1, 5, 12-14). Yeh et al. (13) reported that CTS produced greater changes in ROM and MTU stiffness than CAS in stroke patients with hypertonic ankle plantar flexors. Similar results were shown by Cabido et al. (12) that the changes in ROM and MTU stiffness in the hamstrings in healthy men were greater with CTS than CAS. Other studies have asserted that the reason passive resistive torque decreases with CAS is due to a stress-relaxation response that occurs when muscles are held at constant stretched lengths. In other words, it is due to the viscoelastic properties of muscle (15, 16). Separate studies have shown that maintaining passive resistive torque can cause small increases in joint angle referred to as muscle creep phenomenon (17, 18). This phenomenon is may also be attributed to muscle viscoelasticity, allowing for muscles to be stretched for greater changes in ROM and MTU stiffness (1, 5, 12-14). As such, CTS can be considered an optimal stretching method to promote flexibility and to change the mechanical properties of MTU.

Although a few studies have previously investigated the effects of stretch intensity using CAS (19, 20), none have specifically investigated the influence of CTS on stretch intensity. Freitas et al. (19) compared the influence of different CAS intensities (100 %, 75 %, 50 %) for different lengths of time (5 repetitions of 90 seconds, 135 seconds, and 180 seconds, respectively) on improving peak joint ROM and found that only CAS at 100% for 90 seconds resulted in improved peak joint ROM, while no changes were detected for any of the longer duration submaximal intensity regimes. Recently, the same authors reported that maximum intensity CAS without pain for several 90s repetitions increased maximal ROM, whereas CAS at 50 % intensity for 900 seconds showed no change in maximal ROM (20). The implication of these studies is that CAS at maximum intensity may be the best way to increase joint ROM (19, 20).

With CTS, the initial stretch intensity is considered a crucial factor to maintain constant passive resistive torque throughout the duration of the stretching exercise. Therefore, there is a possibility that CTS at submaximal intensity could improve flexibility and change the mechanical properties of the MTU. It is important to determine the influence of CTS intensity in order to create protocols that will yield improved flexibility and changes to the MTU for injury prevention and rehabilitation. We then hypothesize that higher intensity CTS would induce greater increases in maximal ROM and greater decreases in MTU stiffness. The purpose of the present study was to investigate the effects of CTS intensity on maximal ROM and MTU stiffness.

METHODS

Experimental Approach to the Problem

This randomised crossover study required all participants to perform 5 experimental trials, each 48 hours apart, at the same time of day (± 2 hours) as shown in Figure 1. The first trial orientated and familiarised participants with the instruments throughout the experiment. Passive resistive torque thresholds were then determined. We defined maximal stretch intensity to the point of discomfort but without pain as the passive resistive torque. All participants performed the subsequent four trials, all of which consisted of CTS under the following intensity conditions: no stretching (control), 50 %, 75 %, and 100 % of the passive resistive torque. Each protocol was assigned a number and numbered cards were prepared. Participants were required to pick a card and then perform the protocol corresponding to the number of the card. For the control condition, subjects were instructed to rest for 400 seconds, the duration for all stretching protocols. Maximal ROM and passive resistive torque during passive dorsiflexion of the ankle were measured before and after the CTS for each trial. Participants were asked to relax their ankle plantar flexors during the measurements. Maximal voluntary contraction (MVC) of the ankle plantar flexors was measured after the post-stretching measurements. The temperature in the laboratory room was kept at 25 ˚C.

Figure 1 about here

Participants

Fourteen healthy men (age: 22.9 ± 1.0 years (mean ± SD), height: 174.1 ± 3.9 cm, body mass: 68.6 ± 6.8 kg) with no history of lower-limb injury or neuromuscular disease volunteered for this study through written informed consent. All experiments were conducted on the right plantar flexors of the leg. Participants were asked to refrain from participating in any resistance training or stretching program for twenty-four hours prior to commencement of the interventions and for the entire duration of the study. The ethical committee of a local institutional review board approved the study protocol, and all experimental procedures were performed in accordance with the Declaration of Helsinki.

Flexibility measurements

Maximal ROM and passive resistive torque were determined in pre- and post-stretch protocols using a Biodex System-3 Isokinetic Dynamometer (Biodex Medical System Inc., Shirley, NY, USA) programmed in the passive mode. Participants were secured in the supine position with the right knee in full extension, and the lateral malleolus of the fibula aligned with the axis of the dynamometer. The foot was firmly strapped to a footplate to prevent any movement during ankle dorsiflexion. Investigators used the dynamometer lever arm to dorsiflex passively the ankle from 30 ° plantar flexion at 2 ° per second until maximal dorsiflexion was reached without pain. Participants hold the safety trigger button, which enabled to stop dynamometer in any time. Before any flexibility measurements were conducted, participants maintained a seated position for 10 minutes, then were subjected to three passively performed maximal dorsiflexion for practice. For passive resistive torque, a gravity correction of the limb was performed. Based on methods used in previous studies (21, 22), MTU stiffness was calculated from the inclination angles of the torque-angle curve between 15 ° and 25 ° of ankle dorsiflexion as shown in Figure 3.

Surface electromyography (EMG) was used to ensure the ankle plantar flexors were relaxed during the passive stretching protocols and the flexibility measurements. The skin surface was cleaned with alcohol before bipolar surface electrodes were placed 20 mm apart on the muscle belly of the middle gastrocnemius and connected to an EMG system (MyoSystem 1200, Noraxon USA Inc., Scottsdale, AZ, USA). The root mean square of the EMG activity (within 500 ms) was calculated during MVC of the plantar flexors while the ankle was kept in a neutral position. EMG measurements were taken for all flexibility measurements and stretching protocols at a sampling rate of 1,000 Hz. The EMG activity was calculated as the percentage of maximal voluntary contraction (MVC).

Figure 2 about here

Figure 3 about here

Stretching protocols

Similar to the flexibility protocols, five sets of CTS exercises were each performed for 60 seconds at different intensities using a Biodex System-3 isokinetic dynamometer set to the passive mode. The stretch intensity was determined using the maximum passive resistive torque measured in the first familiarization trial. During the CTS, the dynamometer maintained a constant torque of either 100 % or 75 % or 50 % of the maximal passive resistive torque for 60 seconds and then released to the initial position. A 15-second rest break was taken between each CTS interval. In the control group, the participants were ordered to maintain their leg muscles in a relaxed supine position.

Statistical analysis

Two-way repeated-measures analyses of variance (Stretching intensity × time) were used to determine any significant differences between interventions for maximal ROM and MTU stiffness. Bonferroni's correction was utilized to compare maximal ROM and MTU stiffness between conditions before and after CTS. The significance level was set at $p < 0.05$ and all data were presented as mean ± SE. For the effect size, partial eta-squared values (η^2_p) for repeated measures were calculated. All statistical analyses were performed using SPSS ver. 19.0 (SPSS, Inc., Chicago, Illinois, USA).

RESULTS

EMG activities of the ankle plantar flexors during the flexibility measurements as well as the stretching protocols exhibited less than 10 % MVC. Therefore, based on a previous study (23), muscle activities seem negligible during each experiment and any voluntary contraction torque could be excluded from passive resistive torque in this study. Consequently, all data were utilized for further analyses.

For maximal ROM, a significant two-way interaction (stretching × time) was found ($p < 0.01$, $\eta^2_p = 0.64$). The maximal ROM increased from pre- to post-stretching for 100 % (37.2 ± 6.2 ° to 43.3 ± 6.4 °, $p < 0.01$) and 75 % (35.2 ± 5.3 ° to 39.2 ± 6.7 °, $p < 0.01$), but no significant differences were observed for 50 %（37.3 ± 6.8 ° to 37.8 ± 6.5 °, $p = 0.39$）or the control condition（36.8 ± 6.2 ° to 37.5 ± 5.4 °, $p = 0.14$）. In the pre-stretching, no significant differences in maximal ROM were found among any of the interventions or control conditions. However, CTS at 100 % yielded significantly increased maximal ROM compared to 75 %, 50 % and control ($p < 0.01$, respectively) after stretching, although the results for 75 % and 50 % did not significantly differ from the control ($p = 0.94$~1.00) as shown in Figure.4.

As for MTU stiffness, a significant two-way interaction (stretching × time) was observed, ($p < 0.01$, $\eta^2_p = 0.61$). The MTU stiffness decreased from pre- to post- stretching for 100%（1.3 ± 0.4 Nm / ° to 1.1 ± 0.4 Nm / °, $p < 0.01$）, 75%（1.4 ± 0.4 Nm / ° to 1.3 ± 0.4 Nm / °, $p < 0.01$）and 50 %（1.3 ± 0.5 Nm / °　to 1.3 ± 0.5 Nm / °, $p < 0.01$）, but no differences were observed for the control（1.4 ± 0.5 Nm / °　to 1.4 ± 0.4 Nm / °, $p = 0.57$）. With pre-stretching, no differences were observed among the 100 %, 75 %, 50 % and control conditions. However, CTS at 100 % revealed significantly lower MTU stiffness than 75 %, 50 % and Control ($p < 0.01$ ~ 0.05) after the stretching, whereas no significant differences were found between 75 %, 50 % and Control ($p = 1.00$) as shown in Figure 5.

Figure 4 about here

Figure 5 about here

DISCUSSION

In the present study, we investigated the effects of stretch intensity with CTS on maximal ROM and MTU stiffness to determine whether lower stretch intensity used in combination with a CTS technique could improve flexibility and change the mechanical properties of the MTU. This study showed that CTS at 100 % intensity significantly increased maximal ROM and decreased MTU stiffness in post-stretching compared to CTS at lower intensities and the control condition. While there were no significant differences in maximal ROM and MTU between post-CTS at 50 % or 75 % intensity and the control condition. Therefore, these findings suggested that maximal stretch intensity is required to change both maximal ROM and MTU stiffness of the ankle plantarflexors for CTS techniques.

Recently, many studies have reported that CTS was more effective than CAS to increase ROM and decrease MTU stiffness (1, 5, 12-14). CAS and CTS elicit different viscoelastic responses, e.g. stress relaxation and creep behaviors in muscles. In addition, several studies have reported that when in-vitro animal model muscles (24) and human skeletal muscles (15,16) are held at a stretched length under tensile stress using CAS, a stress relaxation response occurs. Magnusson et al. (15) reported that passive resistive torque during CAS decreased by 30.2 % due to the stress relaxation phenomenon in human skeletal muscles (16). They also revealed that stress relaxation in both healthy and spinal cord-injured subjects lead to a 33.2 % and 38.7 % decrease in passive resistive torque respectively. On the other hand, repeated stretching (10 sets × 30 seconds) in vitro animal models with constant force, increased muscle length and caused creep phenomenon (24). With in vivo testing of skeletal muscles, the majority of muscle creep phenomenon occurred within the first 15 - 20 seconds of CTS (17). With repeated CTS (4 sets × 30 seconds), the extent of the muscle creep phenomenon was the same (18). Therefore, CTS applied at a constant pressure to a muscle causes muscle creep during repeated stretches at the same extent, possibly causing the muscles to work harder than occurs with CAS. Consequently, CTS resulted in greater changes to ROM and MTU stiffness (1, 5, 12-14), implying that CTS is an optimal way of improving flexibility and changing the mechanical properties of the MTU. If considering only MTU work, CTS leads to more work in the same amount of time than CAS, meaning that CTS at submaximal stretch intensities may lead to increased maximal ROM and decreased MTU stiffness. However, whether or not CTS at submaximal intensities affects maximal ROM or MTU stiffness has never been verified and this study is the first to attempt to demonstrate the direct effects of CTS.

The present study showed that only CTS at 100 % intensity significantly increased maximal ROM compared to the control for post-stretch measurements. However submaximal stretch intensities (i.e.75 %, 50 % of the maximal passive resistive torque) had no effect on maximal ROM disproving our hypothesis that submaximal CTS would increase maximal ROM. Freitas et al. (19, 20) compared both stretch intensity and duration using a CAS technique, and reported that higher intensity CAS increased peak joint ROM, while submaximal stretch intensity and longer duration did not. These findings suggest that stretch intensity is more important to increase ROM with CAS.

Our results were obtained using a CTS technique in accordance with previous studies. Thus, stretch intensity can be deemed an important factor for stretch-induced effects, and this study and others support the idea that the initial torque employed during CTS should be as high as possible.

Our data showed a significant decrease in MTU stiffness at 100 % CTS intensity, with no changes at submaximal intensities. To our knowledge, only one other study has investigated the effects of stretch intensity on MTU stiffness with significant decreases resulting from 120 % intensity and not at 80 % (26). Moreover, the change of MTU stiffness at 120 % intensity was greater than at 80 % intensity indicating that higher stretch intensities were necessary to decrease MTU stiffness (26). Many studies reported that longer durations were required to decrease MTU stiffness with CAS whereas CTS decreased MTU stiffness of the calf muscle and hamstring in 30 seconds as well as 60 seconds. As such, it is possible that CTS may require shorter durations to reduce MTU stiffness. In this study, submaximal intensity and longer duration CTS were performed, with no significant changes in MTU stiffness. This is a further indication that the initial stretch intensity is an important factor in decreasing MTU stiffness.

In this study, we did not attempt to show relationship between stretch intensity and flexibility or stiffness of the MTU, although a previous study has postulated that maximal ROM could be influenced by the physiological and neural properties of the MTU (25). In this study, 100 % intensity was defined as the point of discomfort with no pain, something that has been referred to in previous studies. Submaximal intensity did not provide enough stimuli to influence such physiological and neural factors as pain, stretch feeling, stretch tolerance or reflex activity.

Regarding the decrease in MTU stiffness, several studies have investigated the mechanism that decreases MTU stiffness. MTU stiffness decreased after 5 min of stretching due to a decrease in muscle stiffness, not tendon stiffness, estimated by movement of the myotendinous junction (20). Similarly, Kay and Blazevich (27) found that three bouts of 60-second static stretching decreased muscle stiffness while tendon stiffness was unchanged. Therefore, the decrease in MTU stiffness after stretching was due to a decrease in muscle stiffness but not tendon stiffness. Notably, Gajdosik et al. (28) suggested that connective tissues such as the endomysium, perimysium and epimysium could be responsible for any changes in passive stiffness. In the present study, decreases in MTU stiffness might have been caused by increased extensibility in intramuscular connective tissues such as those listed above. Future studies should examine the mechanisms concerned with stretching intensity and the mechanical properties of MTU.

There were several methodological limitations in this study. First, the present study did not examine the influence of the stretching duration. Future studies should be conducted to clarify the interaction of stretching intensity and duration focusing on the mechanical properties of MTU. Second, in this study, MTU stiffness was calculated based on torque-angle curve. As such, we could not detect which tissues were affecting stiffness, as the MTU is made up of muscle, tendon, fascia, and connective tissue. Ultrasound images and elastographic techniques would provide more detailed information and might be useful for estimating the effects on mechanical properties of muscle and tendon separately.

PRACTICAL APPLICATION

The present study determined that CTS at 100% intensity increased ROM and decreased MTU stiffness compared with the control condition. These findings indicate that the highest stretching intensity is recommended to improve both flexibility and MTU stiffness. Therefore, coaches, trainers and therapists should consider stretch intensities, durations, frequencies, positions and technique could affect stretching results (11, 12).

REFERENCES

1) Herda TJ, Costa PB, Walter AA, Ryan ED, Cramer JT. The time course of the effects of constant-angle and constant-torque stretching on the muscle-tendon unit. *Scand J Med Sci Sports* 24: 62-7, 2014.
2) Bandy, W.D. and Irion, J.M. The effect of time on static stretch on the flexibility of the hamstring muscles. *Phys Ther* 74: 845-852, 1994.
3) Bandy, W.D., Irion, J.M., and Briggler, M. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys Ther* 77: 1090-1096, 1997.
4) Taniguchi K, Shinohara M, Nozaki S, Katayose M. Acute decrease in the stiffness of resting muscle belly due to static stretching. *Scand J Med Sci Sports* 25: 32-40, 2015.
5) Herda TJ, Costa PB, Walter AA, Ryan ED, Hoge KM, Kerksick CM, Stout JR, Cramer JT. Effects of two modes of static stretching on muscle strength and stiffness. *Med Sci Sports Exerc* 43: 1777-84, 2011.

6) Ryan ED, Beck TW, Herda TJ, Hull HR, Hartman MJ, Costa PB, Defreitas JM, Stout JR, Cramer JT. The time course of musculotendinous stiffness responses following different durations of passive stretching. *J Orthop Sports Phys Ther* 38: 632-9, 2008.

7) Ryan ED, Herda TJ, Costa PB, Defreitas JM, Beck TW, Stout J, Cramer JT. Determining the minimum number of passive stretches necessary to alter musculotendinous stiffness. *J Sports Sci* 27: 957-61, 2009.

8) Smith CA. The warm-up procedure: to stretch or not to stretch. A brief review. *J Orthop Sports Phys Ther* 19: 12-7, 1994.

9) Shellock FG, Prentice WE. Warming-up and stretching for improved physical performance and prevention of sports-related injuries. *Sports Med* 2: 267-78, 1985.

10) Safran MR, Seaber AV, Garrett WE Jr. Warm-up and muscular injury prevention. An update. *Sports Med* 18: 239-49, 1989.

11) Apostolopoulos N, Metsios GS, Flouris AD, Koutedakis Y, Wyon MA. The relevance of stretch intensity and position-a systematic review. *Front Psychol* 18: 1128, 2015.

12) Cabido CE, Bergamini JC, Andrade AG, Lima FV, Menzel HJ, Chagas MH. Acute effect of constant torque and angle stretching on range of motion, muscle passive properties, and stretch discomfort perception. *J Strength Cond Res* 28: 1050-7, 2014.

13) Yeh CY, Chen JJ, Tsai KH. Quantifying the effectiveness of the sustained muscle stretching treatments in stroke patients with ankle hypertonia. *J Electromyogr Kinesiol* 17: 453-61, 2007.

14) Yeh CY, Tsai KH, Chen JJ. Effects of prolonged muscle stretching with constant torque or

constant angle on hypertonic calf muscles. *Arch Phys Med Rehabil* 86: 235-41, 2005.

15) Magnusson SP, Simonsen EB, Aagaard P, Kjaer M. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. *Am J Sports Med* 24: 622-8, 1996.

16) Magnusson SP, Simonsen EB, Dyhre-Poulsen P, Aagaard P, Mohr T, Kjaer M. Viscoelastic stress relaxation during static stretch in human skeletal muscle in the absence of EMG activity. *Scand J Med Sci Sports* 6: 323-8, 1996.

17) Ryan ED, Herda TJ, Costa PB, Walter AA, Hoge KM, Stout JR, Cramer JT. Viscoelastic creep in the human skeletal muscle-tendon unit. *Eur J Appl Physiol* 108: 207-11, 2012.

18) Ryan ED, Herda TJ, Costa PB, Walter AA, Cramer JT. Dynamics of viscoelastic creep during repeated stretches. *Scand J Med Sci Sports* 22: 179-84, 2012.

19) Freitas SR, Vilarinho D, Rocha Vaz J, Bruno PM, Costa PB, Mil-homens P. Responses to static stretching are dependent on stretch intensity and duration. *Clin Physiol Funct Imaging* 35: 478-84, 2014.

20) Freitas SR, Vaz JR, Bruno PM, Andrade R, Mil-Homens P. Stretching Effects: High-intensity & Moderate-duration vs. Low-intensity & Long-duration. *Int J Sports Med* 37: 239-44, 2016.

21) Morse CI, Degens H, Seynnes OR, Maganaris CN, Jones DA. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. *J Physio* 586: 97-106, 2008.

22) Nakamura M, Ikezoe T, Takeno Y, Ichihashi N. Acute and prolonged effect of static stretching on the passive stiffness of the human gastrocnemius muscle tendon unit in vivo. *J Orthop Res*

29: 1759-63, 2011.

23) Trajano GS, Nosaka K, B Seitz L, Blazevich AJ. Intermittent stretch reduces force and central drive more than continuous stretch. *Med Sci Sports Exerc* 46: 902-10, 2014.

24) Taylor DC, Dalton JD Jr, Seaber AV, Garrett WE Jr. Viscoelastic properties of muscle-tendon units. The biomechanical effects of stretching. *Am J Sports Med* 18: 300-9, 1990.

25) Blazevich AJ, Cannavan D, Waugh CM, Fath F, Miller SC, Kay AD. Neuromuscular factors influencing the maximum stretch limit of the human plantar flexors. *J Appl Physiol* 113: 1446-55, 2012.

26) Kataura S, Suzuki S, Matsuo S, Hatano G, Iwata M, Yokoi K, Tsuchida W, Banno Y, Asai Y. Acute effects of the different intensity of static stretching on flexibility and isometric muscle force. *J Strength Cond Res* 31: 3403-3410, 2016.

27) Kay AD, Blazevich AJ. Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. *J Appl Physiol* 106: 1249-56, 2009.

28) Gajdosik RL. Passive extensibility of skeletal muscle review of the literature with clinical implications. *Clinical Biomechanics* 16: 87-101, 2001.

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FIGURE LEGENDS

Figure 1. Experimental design.

Figure 2. Experimental setup for flexibility measurement and stretching protocols.

Figure 3. An example of torque-angle curve and determination of MTU stiffness.

Figure 4. Mean values ± SE for dorsiflexion angle in pre- and post-stretching with each stretching condition.

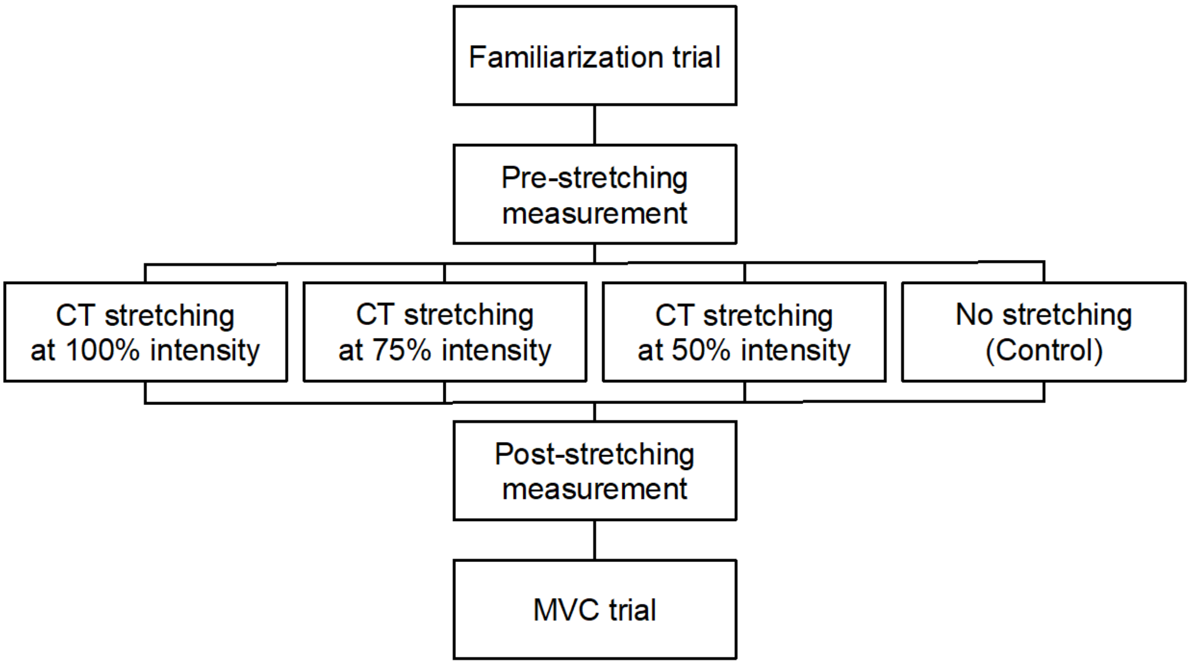
#: Significant difference from pre- to post-stretching ($p<0.05$).

† : Significant difference from the control, 75%, 50% with post-stretching ($p<0.05$).

Figure 5. Mean values ± SE for MTU stiffness in pre- and post-stretching with each stretching condition.

#: Significant difference from pre- to post-stretching ($p<0.05$).

†: Significant difference from the control, 75%, 50% with post-stretching ($p<0.05$).



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337 **Figure 1**

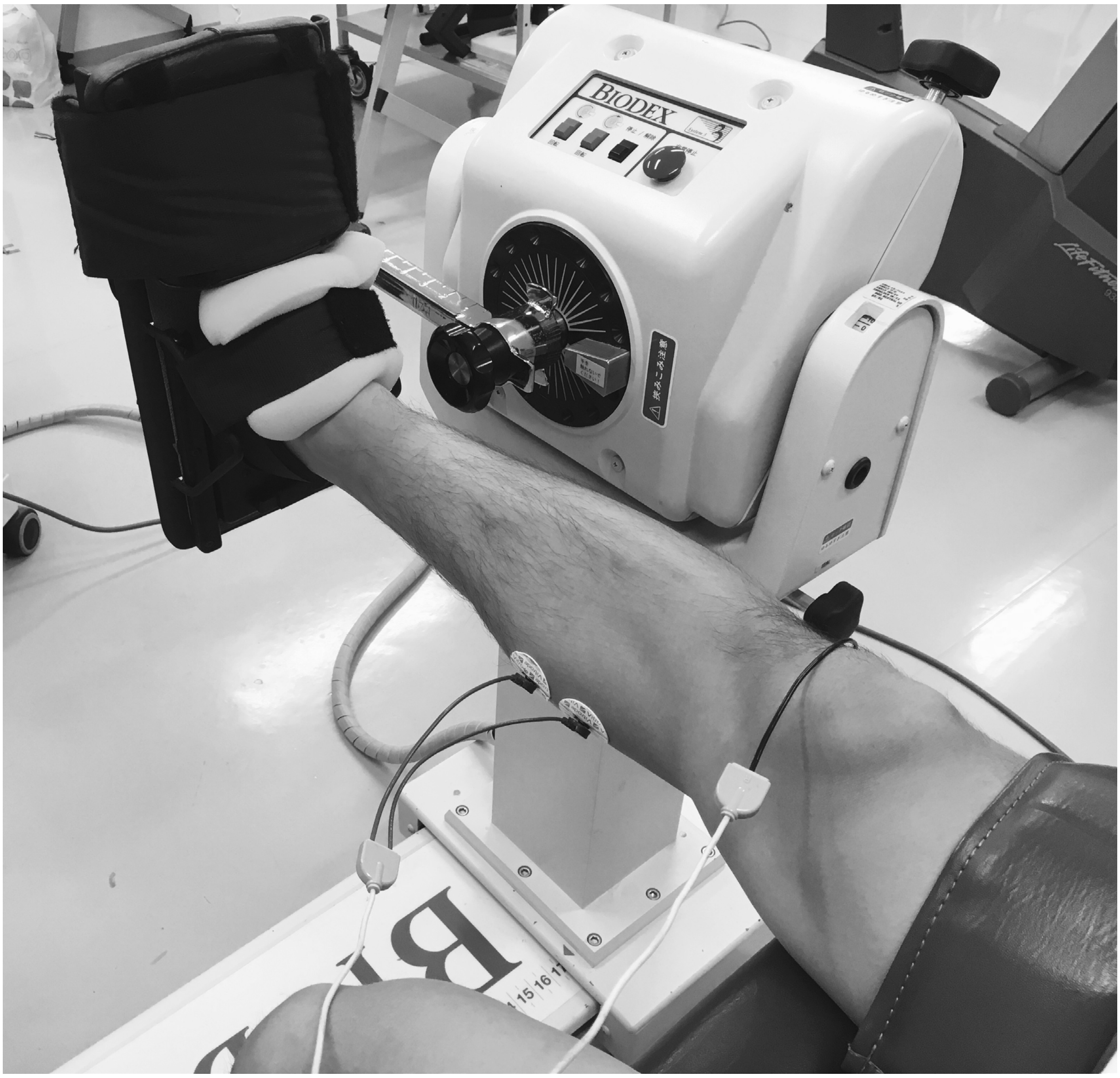

Figure 2

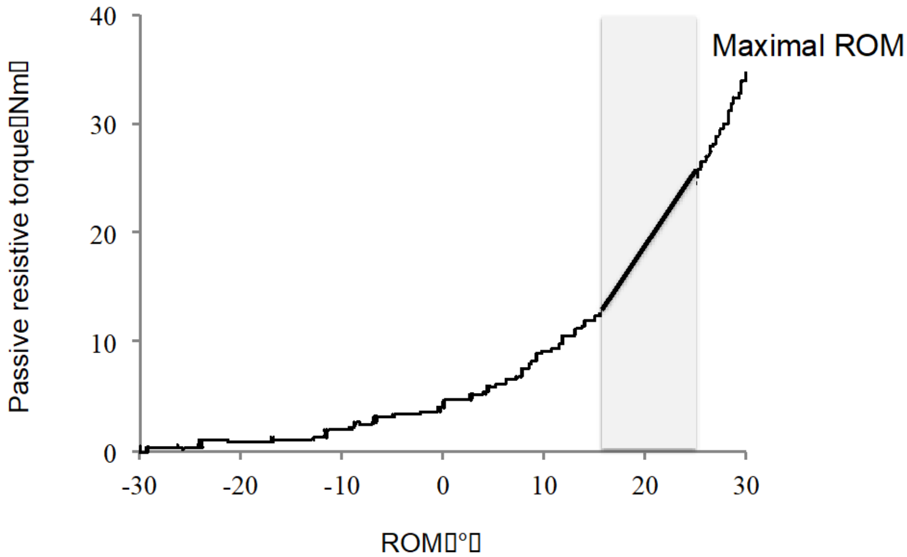
Passive resistive torque（Nm）
40
30
20
10
0
-30
-20
-10
0
10
20
30
ROM（°）
Maximal ROM

Figure 3

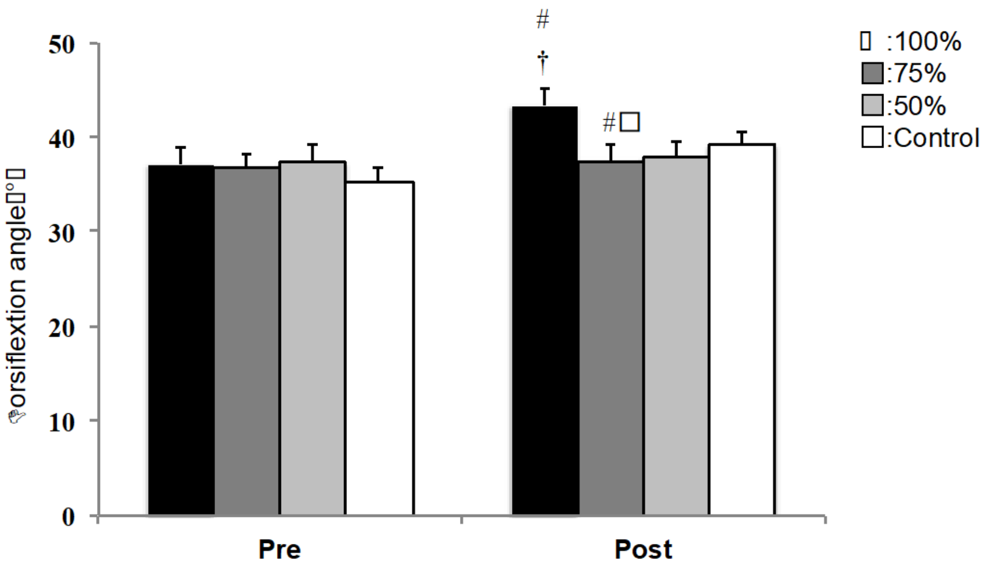

Figure 4

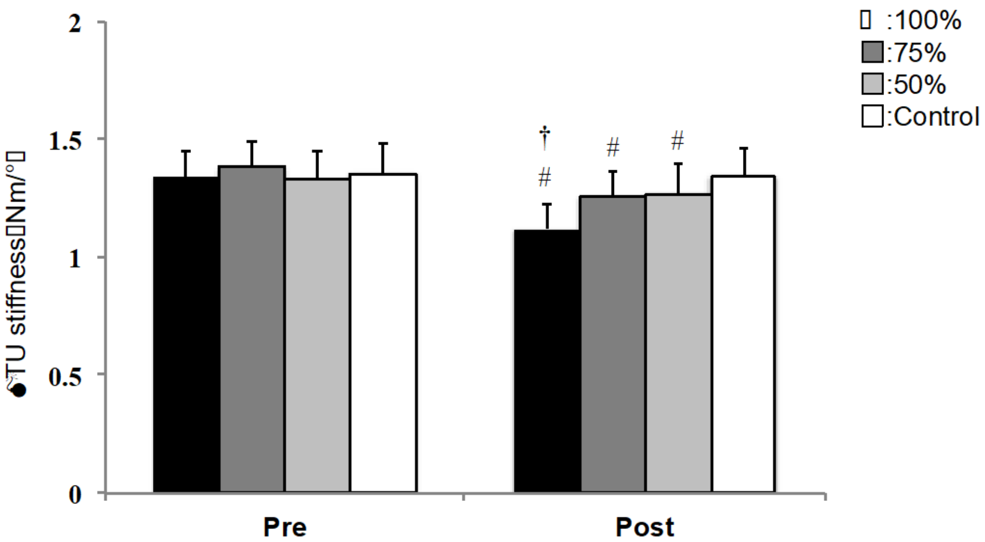

Figure 5