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Research article

The Acute Effects of Static and Cyclic Stretching on Muscle Stiffness and Hardness of Medial Gastrocnemius Muscle

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Abstract

This study aimed to clarify the acute effects of static stretching (SS) and cyclic stretching (CS) on muscle stiffness and hardness of the medial gastrocnemius muscle (MG) by using ultrasonography, range of motion (ROM) of the ankle joint and ankle plantar flexor. Twenty healthy men participated in this study. Participants were randomly assigned to SS, CS and control conditions. Each session consisted of a standard 5-minute cycle warm-up, accompanied by one of the subsequent conditions in another day: (a) 2 minutes static stretching, (b) 2 minutes cyclic stretching, (c) control. Maximum ankle dorsiflexion range of motion (ROM max) and normalized peak torque (NPT) of ankle plantar flexor were measured in the pre- and post-stretching. To assess muscle stiffness, muscle-tendon junction (MTJ) displacement (the length changes in tendon and muscle) and MTJ angle (the angle made by the tendon of insertion and muscle fascicle) of MG were measured using ultrasonography at an ankle dorsiflexion angle of −10°, 0°, 10° and 20° before and after SS and CS for 2 minutes in the pre- and post-stretching. MG hardness was measured using ultrasound real-time tissue elastography (RTE). The results of this study indicate a significant effect of SS for ROM maximum, MTJ angle (0°, 10°, 20°) and RTE (10°, 20°) compared with CS ($p < 0.05$). There were no significant differences in MTJ displacement between SS and CS. CS was associated with significantly higher NPT values than SS. This study suggests that SS of 2 minutes' hold duration significantly affected muscle stiffness and hardness compared with CS. In addition, CS may contribute to the elongation of muscle tissue and increased muscle strength.

Key words: Static stretching, cyclic stretching, muscle stiffness, muscle hardness, real-time tissue elastograpy.

Introduction

Stretching improves skeletal muscle flexibility and physical performance. Sports activities specialized stretching has yielded the most important outcomes in relation to preventing injuries (Lewis 2014; Zakaria et al., 2015).

Typically, static stretching (SS), which holds the muscles at extended positions without recoil, is used for improving muscle flexibility. SS is widely used in warm-up routines in athletic practice or competitions because it is easy and safe. However, previous research shows SS decreases muscle power and subsequent performance (Behm and Chaouachi 2011; Behm et al. 2016; Kay and Blazevich 2012). In contrast, previous studies reported that DS may increase muscle strength and physical performance when the DS period is extended (Ryan et al., 2010; Yamaguchi et al. 2007). However, DS may not be as effective as SS in increasing muscle viscoelasticity in a single warm-up session (Behm and Chaouachi 2011; Behm et al. 2016).

McNair et al. (2001) found that constant velocity stretching (cyclic stretching, CS) decreases muscle stiffness by decreasing the dynamic torque at the same angular velocity. CS involves moving the joint at a constant angle and rate using a dynamometer and a continuous passive motion device (Nordez et al., 2009). Previous studies have shown that the passive torque and stiffness are altered immediately after cyclic stretching protocols (Magnusson et al., 1998; McNair et al., 2001; Nordez et al., 2008). Moss et al., (2011) reported that a drop landing was not influenced by SS. Furthermore, we found that dynamic balance after jump and landing was not affected by SS, but CS was suggested to improve dynamic balance ability (Maeda et al., 2016). However, to our knowledge, the characteristics and differences between SS and CS have not been previously investigated using ultrasonography in healthy men. Especially, it is unknown whether or not an acute effect of cyclic stretching changes the passive fascicle stiffness of medial gastrocnemius muscle (MG). This study aimed to clarify the acute effects of SS and CS on muscle stiffness and hardness of MG by using ultrasonography and measuring muscle strength. Muscle stiffness is defined as the ratio of change in force to change in length along the longitudinal axis of muscle (Murayama et al., 2005), while muscle hardness is defined as the resistance that muscle exerts on vertical pressure (Alamäki et al., 2007). We hypothesized that SS decreases muscle stiffness and hardness compared with CS. However, CS decreases muscle hardness compared with the control condition and maintains muscle power compared with SS.

Methods

Participants

A total of 20 healthy, recreationally active men (mean, SD: age 22.8 ± 1.4 years; height, 1.70 ± 0.01 m; body mass 63.4 ± 8.3 kg) voluntarily participated in the study.

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“Recreationally active” was defined as participation in at least one exercise session per week in the preceding two months, and no involvement in any structured power or flexibility training during this period (Costa et al., 2009). Subjects were excluded if they had current ligamentous defects, history of a sprain of grade II or worse, history of ligament or joint reconstruction or repair, trauma (including fracture, myositis ossificans or burns), or dysfunction of the vestibular system affecting balance. The subjects performed three different protocols (CS, SS and control) in randomly on three separate days, with an interval of at least 24 h and no more than 48 h between tests. All subjects were able to complete the study. The average duration of each condition was 52.0±3.0 minutes.

The power for each analysis of variance was not less than 0.65 for an effect size of more than 0.80 (Cohen, 1998). A priori power analysis by G*power revealed that a static power of 0.75 at an effect size of 0.80 with an alpha level of 0.05 required a sample size of at least 20 subjects.

This study was approved by the Center for Integrated Medical Research of Hiroshima University (study protocol ID number: E-341), and all subjects gave informed consent to participate in the study.

Experimental design and procedures

Subjects were assigned to three randomly ordered experimental conditions (SS, CS, and control) and their order was counter-balanced across subjects. Limb stretching was performed on the non-dominant limb for unilateral assessment to assure consistency in data collection among the subjects (Hicks et al., 2016). The non-dominant limb was defined as the limb that was not used to kick a soccer ball; all subjects were determined to be right-leg dominant.

Stretching conditions were randomly performed by all subjects with their hips and knees in full extension while prone on a footplate with the ankle at an angle of −10° (10° of plantarflexion: control condition) or at maximum dorsiflexion (SS condition). For the CS condition, a stretching device with a Biodex III dynamometer (Sakai Medical Co., Ltd., Tokyo, Japan) was used to produce cycles at 10°/s with the ankle moving from plantarflexion to 80% of maximum dorsiflexion. McNair (2002) reported that CS from 0 to 80% of maximum dorsiflexion does not evoke a stretch reflex Therefore, stretching with the ankle at 80% of maximum dorsiflexion was used in the current study. The stretching time was based on the findings of Kanazawa et al. (2009) showing that maximum dorsiflexion reached a plateau after 2 minutes when both the gastrocnemius and Achilles tendons underwent SS at maximum dorsiflexion in a prone position.

Surface electromyographic signals (sEMG) of lateral gastrocnemius muscle were also recorded synchronously with the torque and angle data to ensure that no undesirable activation occurred during the stretching protocol.

Assessment of maximum ankle dorsiflexion range of motion

To determine the effect of stretching in each stretching condition, we measured the degree of maximum ankle dorsiflexion range of motion (ROM max) pre and post-stretching of SS, CS and control protocols. The subjects were placed in the prone position, with the knee fully extended on the examination bed. Measurement of the degree of passive dorsiflexion after each condition was performed three times using a Biodex III that was programmed to automatically move the footplate according to angle measurements. The average of the 3 trials was used as the measurement value. The maximum degree of ankle dorsiflexion was defined as the angle at which the subjects started to feel discomfort or painful.

Assessment of normalized peak torque of plantar flexor

Subjects lay on a Biodex III bed in prone position with 0˚ hip and knee angles, and their non-dominant feet were firmly fixed at 0˚ to the footplate with two non-elastic straps. Normalized peak torque in ankle plantar flexion power was exerted by the ankle plantar flexor muscles with the maximum force held for 3 s. For all subjects, isometric muscle power measurements were performed three times for the non-dominant leg. The average of the 3 trials was used as the measurement value. Subjects rested for 1 minute after each test to avoid fatigue. Subjects were advised to give maximal effort with verbal encouragement from the investigator during each measurement. Previous research has demonstrated excellent reliability for this test, with intra-class correlation coefficient test-retest values between 0.94 and 0.99 for isometric dynamometers (Webber and Porter 2010).

Assessment of B-mode ultrasonography and real-time tissue elastography

Axial B-mode and real-time tissue elastography (RTE) images of the non-dominant MG were obtained before and after each stretching condition using a digital ultrasound system (HI VISION Avius; Hitachi Aloka Medical Japan, Tokyo, Japan) with a 14–16 MHz linear array transducer (EUP-L65; Hitachi Aloka Medical Japan). As reference material, an acoustic coupler (EZU-TECPL1; Hitachi Aloka Medical Japan) was placed onto the transducer with a plastic attachment (EZU-TEATC1; Hitachi Aloka Medical Japan). The elasticity of the acoustic coupler was 22.6±2.2 kPa according to material testing performed by the manufacturer.

Assessment of muscle stiffness

The muscle-tendon junction (MTJ) displacement and angle for evaluating muscle stiffness were measured and visualized as a continuous sagittal plane ultrasound image using an 8-MHz linear array probe. An acoustically reflective marker was placed on the skin under the ultrasound probe to confirm that the probe did not move during measurement (Maganaris, 2005; Morse et al., 2008). The probe was fixed with a manual fixed frame fixed with tape to the surface of the target muscle.

Ultrasound images of the MTJ displacement and angle were quantified using open-source digital measurement software (ImageJ, National Institutes of Health, Bethesda, MD, USA). For accuracy in measurement, MTJ was identified at the innermost edges of the fascia surrounding the muscle where it fuses with the tendon. MTJ displacement was measured every 10° from 0° to 20° of ankle dorsiflexion and the magnitude of change for each angle from a reference value of −10° was calculated. MTJ angle was made by the tendon of insertion and muscle fascicle (MTJ angle) of MG (Kumamoto et al. 2007) and measured every 10° from 0° to 20° after each condition was performed.

Assessment of muscle hardness using real-time tissue elastography

In this study, the location of the ultrasound probe was adjusted on a line drawn on the muscle belly of the MG (70% of the distance between the medial point of the knee joint space and the central point of the medial malleolus) so that we could scan the centre region of the MG. The location of the probe was marked with semi-permanent ink on the skin surface and redrawn when fading. The probe was consistently placed on the mark so that RTE measurement was performed at the same position for every measurement. The scanning head of the probe was coated with transmission gel to obtain acoustic coupling.

RTE images were obtained by manually applying light repetitive compression (rhythmic compression-relaxation cycle) with the transducer in the scan position. To obtain appropriate images for investigation, we applied the transducer with constant repeated pressure, monitoring the pressure indicator incorporated into the ultrasound scanner. The RTE image appeared as a translucent, color-coded, real-time image superimposed on the B-mode image. The scale ranged from blue for components with less strain (i.e., the hardest components) to red for components with greater strain (i.e., the softest components). Green indicated average strain. The sharpest (clearest) is checked in scanning process. The mean strain in the region of interest (ROI) was monitored in a strain graph to adjust and maintain the force and frequency of the compression. The frequency was adjusted from 2 Hz to 4 Hz depending on each individual and condition so that the elastogram was sufficiently superimposed on the ROI. The strain rate within each ROI was automatically measured using built-in software, and the strain ratio (reference/muscle ratio, i.e. the strain measured in the ROI of the reference divided by the strain in the ROI of the muscle) was calculated for each image. The RTE in response to the compression force is physically smaller in harder tissue than in softer tissue. Therefore, as the muscle becomes harder, the value of RTE decreases. RTE measurements were performed three times, and the mean values were calculated. The same examiner positioned all ROIs and performed all measurements. High intra-observer reproducibility has been previously shown in the muscle/reference ratio of three repeated RTE measurements (Yanagisawa et al., 2011).

Statistical analysis

Repeated-measures 2 (time) × 3 (stretching condition) analysis of variance (ANOVA) model was used for comparisons of changes in ROM in both stretching conditions (SS and CS) and the control condition. When appropriate, follow-up analyses were performed using paired t-tests between pre- and post- stretching to confirm significant changes within each condition. A repeated-measures 1 (time) × 3 (stretching condition) analysis of variance (ANOVA) model was used for comparisons of ROM max, NPT, MTJ displacement, MTJ angle and RTE between both stretching conditions (SS and CS) and the control condition. When appropriate, follow-up analyses were performed using Bonferroni post hoc tests. An alpha level of .05 was the criterion for rejection of the null hypothesis for all statistical tests. Effect sizes were calculated using the Cohen d statistic. The intraclass correlation coefficient ($ICC_{1,3}$) was used to assess intraobserver reliability. The $ICC_{1,3}$ was calculated for MTJ displacement, MTJ angle and RTE in the control condition. Effect size was calculated using the formula $f = d^{*} \sqrt{1/2k}$, where $d = (m_{max} - m_{min})/\sigma$ and k = the number of treatments. Observed power was generated by SPSS software. Data analysis was conducted using SPSS for Windows, v. 23.0 (IBM Japan Co., Tokyo, Japan).

Results

The $ICC_{1,3}$ values of MTJ displacement, MTJ angle and RTE from 0° to 20° in the control condition are shown in Table 1. Overall, intraobserver reliability of MTJ displacement, MTJ angle and RTE were high. The range of $ICC_{1,3}$ values observed was 0.99–1.00 for MTJ displacement, 0.92–0.99 for MTJ angle and 0.90–0.99 for RTE.

Table 1. $ICC_{1,3}$ values of MTJ displacement, angle and RTE

	Angle (deg)	Intraclass correlation $ICC_{(1,3)}$	95% CI
MTJ displacement (mm)	0	1.00	(0.99-1.00)
	10	1.00	(0.99-1.00)
	20	1.00	(0.99-1.00)
MTJ angle (°)	0	0.98	(0.97-0.99)
	10	0.96	(0.92-0.98)
	20	0.97	(0.94-0.99)
RTE (muscle/coupler)	0	0.97	(0.93-0.99)
	10	0.99	(0.97-0.99)
	20	0.95	(0.90-0.98)

Intraobserver reliability of Muscle-Tendon Junction (MTJ) displacement, MTJ angle and real time tissue elastography were high. The range of $ICC_{1,3}$ values observed was 0.99-1.00 for MTJ displacement, 0.92-0.99 for MTJ angle and 0.90-0.99 for RTE.

Repeated-measures ANOVA did detect significant intervention (stretching condition)×time (pre- and post-intervention) interaction ($p < 0.01$). The paired t-test analyses indicated that SS and CS condition significantly between pre and post-stretching. The angle and change in range of dorsiflexion pre and post-stretching are shown in Table 2.

ROM max, NPT, MTJ displacement, MTJ angle and RTE after the three conditions are shown in Tables 3 and 4. The value of ROM max after SS was significantly higher than after CS and control. The value of ROM max after CS was significantly higher than after control. NPT after CS was significantly higher than after SS. MTJ displacement of 0°, 10° and 20° after SS was significantly higher than after control. MTJ displacement of 10° and 20° after CS was significantly higher than after control. MTJ angle of 0°, 10° and 20° after SS was significantly lower than after CS. RTE of 0° after SS and CS was significantly higher than after control. RTE of 10° and 20° after SS was significantly higher than after CS and control. RTE of 0° and 20° after CS was significantly higher than after control.

Table 2. Change in range of motion control between pre and post-measurement. Data are means (±SD).

Ankle dorsiflexion (°)	Pre	Post
Control	24.6 (2.6)	24.4 (2.4)
SS	24.8 (2.8)	29.4 (3.4) *
CS	24.7 (2.8)	28.4 (3.5) *

Control, control condition; SS, static stretching; CS, cyclic stretching.
* Indicates a significant difference between pre and post-measurement for SS and CS ($p < 0.05$).

Table 3. Values for ROM max, NPT of Gastrocnemius Muscle according to each stretching condition. Data are means (±SD).

Variables	Condition			P-value	Effect Size	Observed Power
	Control	SS	CS			
ROM max (°)	24.7 (2.7)	29.4 (3.4)	28.4 (3.5)	SS > CS > Control †	0.93	1.00
NPT of Plantar Flexor (Nm/kg)	1.18 (.34)	1.12 (.32)	1.27 (.32)	**CS > SS ††**	0.25	0.88

Dorsiflexion range of motion max (ROM max) and Normalized Peak Torque (NPT) after each stretching condition. Significant increases in dorsiflexion ROM max were found after Static Stretching (SS) and cyclic stretching (CS) compared with control condition. Significant increases in NPT were found after CS compared with SS. † Indicates a significant difference in each condition ($p < 0.05$). †† Indicates a significant difference after SS compared with CS ($p < 0.01$).

Table 4. Values for ⊿MTJ displacement, MTJ angle, RTE of medial gastrocnemius muscle according to each stretching condition. Data are means (±SD).

Variable	Angle (deg)	Condition				Effect Size	Observed Power
		Control	SS	CS	P-value		
MTJ displacement (mm)	0	3.77 (2.04	4.77 (1.48)	5.06 (2.12	SS > Control †	0.34	0.71
	10	8.28 (1.78)	9.85 (1.26)	9.79 (1.60	SS > Control †† CS > Control †	0.52	0.96
	20	12.07(1.78)	14.07 (1.55)	13.39 (1.70)	SS > Control †† CS > Control †	0.53	0.97
MTJ angle (°)	0	10.32 (2.30)	9.35 (2.05)	10.25 (2.16)	Control > CS > SS ††	0.93	1.00
	10	8.37 (1.78)	7.63 (1.67)	9.38 (2.35)	CS, Control > SS ††	0.53	0.97
	20	7.03 (1.59)	6.12 (1.51)	8.43 (1.96)	**CS > Control > SS ††**	0.77	1.00
RTE (muscle / coupler)	0	21.95 (3.07)	24.78 (3.23)	24.01 (3.06)	SS > Control †† CS > Control ††	0.75	1.00
	10	8.34 (2.16)	11.62 (3.03)	10.51 (2.59)	**SS > CS > Control ††**	0.77	1.00
	20	1.90 (.55)	3.29 (0.93)	2.69 (0.96)	**SS > CS > Control ††**	0.78	1.00

Muscle-Tendon Junction (MTJ) displacement, MTJ angle, and Real-time tissue elastgraphy (RTE) after each stretching condition. Significant changes in MTJ angle (0°, 10°, 20°) and RTE (0°, 10°, 20°) were found after Static Stretching (SS) stretching compared with and cyclic stretching (CS). There were no significant differences in MTJ displacement between SS and CS. † Indicates a significant difference in each condition ($p < 0.05$). †† Indicates a significant difference after SS compared with CS ($p < 0.01$).

Discussion

The aim of this study was to examine the acute effects of stretching MG of the non-dominant limb on muscle stiffness and hardness, dorsiflexion angle and isometric muscle power, after SS with the ankle, CS at a repeated constant velocity of 10°/s, or no stretching intervention (control) for 2 minutes. The degree of ROM max was significantly increased after SS and CS compared with the control condition. Siatras et al. (2008) found that the ankle ROM increased significantly after SS of more than 30 s. Previous studies have also shown that ROM max increased significantly after SS and CS (Avela et al. 1999; Chaouachi et al. 2017; Ryan et al. 2010; Witvrouw et al. 2004). Thus, the findings of the present study are similar to those of previous studies. Furthermore, ROM max after SS was significantly increased compared with CS.

However, the current study was not clear the physiological reason that there was significant difference between SS and CS. After SS, Nakamura et al. (2011) reported that decrease of muscle stiffness was caused by increasing the flexibility and movement of the aponeurosis and the connective tissue, e.g., endomysium, perimysium, and epimysium, instead of lengthening muscle fiber. After CS, previous study reported that bonds between actin and myosin filament contributed to the muscle passive tension, and these bonds were broken by increasing muscle length on using short-range experiments in isolated muscle (Proske et al. 1999; Whitehead et al. 2001). In addition, changes in structural arrangement of muscle could possibly occurred during motion and induce muscle thixotropy. For example, more mobile constituents such as the polysaccharides and water might be redistributed during cyclic stretching (McNair et al. 2001). It was considered that difference in the ROM between conditions due to the difference of mechanism in decreasing the muscle stiffness.

NPT of the plantar flexor was significantly higher after CS compared with SS. CS tended to increase NPT compared with the control condition. McNair et al. (2001) reported that dynamic torque and muscle stiffness were maintained after CS but not after SS. Additionally, Çelik (2017) reported an increase in muscle strength after CS for volleyball players. This study's results suggest that CS may be beneficial, as it increases both flexibility and strength in MG of young males. Therefore, CS may contribute not only to flexibility but also to increase in muscle strength.

MTJ displacement and RTE were significantly increased after SS and CS compared with the control condition. Furthermore, MTJ angle (each angle) and RTE (10°, 20°) after SS were significantly different compared with CS. Decreased muscle stiffness after SS was also reported by Kay et al. (2015). In the present study, RTE and MTJ angle after CS was significantly higher than the control condition. This indicates that CS decreases muscle stiffness and hardness, and suggests the possibility of CS being stretching method that does not further decrease muscle strength. Bressel et al. (2002) showed that torque relaxation for prolonged interventions is greater after SS than after CS. Thus, this is the first study to show an acute effect of CS of decreased muscle stiffness and hardness with increased muscle power compared with SS.

A few limitations of the present study need to be considered. It had a small sample size; future epidemiological studies should be conducted in a consistent way with a large number of participants. Second, despite the fact that MG and lateral gastrocnemius muscle are the two-joint muscles that intersect for the knee and ankle joints, passive elongation and stretching are performed only in the knee extension position. Thus, it is unclear whether the differences in passive muscle stiffness between MG and LG in the knee extended position can be observed in the knee flexed position. Finally, the acute effects after SS and CS stretching were examined, not the long-term effect. Previous studies have examined the effects of long-term SS or CS on joint ROM (Gajdosik et al., 2007), but there are few reports on the difference in the effects of intervention of SS versus CS on muscle stiffness, hardness and power. Further studies are needed to verify the effects of long-term SS and CS. More detailed examination of the effects of different stretching-speed changes of CS on the viscoelastic properties of connective tissues surrounding the muscles is also required.

Conclusions

This study examined the effects of SS and CS on ROM, NPT, muscle stiffness and hardness. The results indicate that the ROM max after SS was significantly greater compared with CS and Control. NPT after CS was significantly higher than after SS. A significant decrease in muscle stiffness and hardness after SS was observed compared with CS. However, CS suggests the possibility of being a muscle stiffness method that does not further decrease muscle power.

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Key points

- This study examined the acute effects of static and cyclic stretching on muscle stiffness and hardness
- SS of 2 minutes' hold duration significantly affected in muscle stiffness and hardness compared with CS.
- CS may contribute to the elongation of muscle tissue and increased muscle strength.

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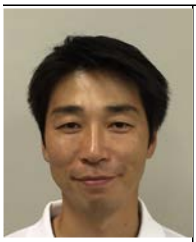

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