Effects of short-duration constant torque and constant angle stretching on the musculotendinous stiffness of ankle plantar flexors

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ABSTRACT

Purpose: This study aimed to investigate and compare the time-course effects of four repeated 30-second constant torque stretching (CTS) and constant angle stretching (CAS) on the musculotendinous stiffness (MTS) of ankle plantar flexors.

Methods: Employing a crossover design, this study included 21 healthy young males who underwent CTS and CAS in a randomized order. Each stretching condition comprised four sets of 30-second stretches separated by 20-second rest intervals. MTS was measured using torque-angle curves before and after each set.

Results: Two-way repeated-measures analysis of variance (ANOVA) revealed a significant interaction effect between the stretching condition and time on MTS (p=0.03). While both CTS and CAS significantly reduced MTS after each set, greater reductions were observed in CTS across all sets.

Conclusion: This study suggests that CTS is an effective stretching technique for significantly reducing the MTS of ankle plantar flexors within a short duration of time, indicating its utility in warm-up exercises and rehabilitation programs.

Keywords

Static stretching, flexibility, warming up, injury prevention, stretch intensity

Abbreviation

Static stretching (SS), range of motion (ROM), musculotendinous stiffness (MTS), constant angle stretching (CAS), constant torque stretching (CTS), standard deviation (SD), analysis of variance (ANOVA), intraclass correlation coefficients (ICC), standard error of measurement (SEM), coefficient of variation (CV)

INTRODUCTION

Static stretching (SS) is fundamental technique that involves holding the muscle group in a lengthened position at the end of its range of motion (ROM) for a sustained period. Due to its simplicity, SS is widely implemented in clinical and athletic settings. Musculotendinous stiffness (MTS), calculated as the slope of the passive torque-joint angle relationship, is a biomechanical property reflecting the resistance of the musculotendinous complex to stretch, making it an objective measure of musculotendinous extensibility compared to traditional ROM measurements [1, 2]. Research shown that SS protocols can effectively decrease MTS scores [3–5]. In daily activities and sports, increased muscle stiffness and MTS are associated with increased metabolic and energy expenditure during movement, postural control, and greater risk of muscle strain injuries [6, 7]. Effective stretching protocols to reduce MTS are therefore crucial for optimizing sports performance and rehabilitation programs.

SS is primarily classified into two techniques: constant angle stretching (CAS) and constant torque stretching (CTS). CAS involves maintaining the joint angle at the end of the ROM during the stretch, resulting in a constant musculotendinous complex length. This approach induces a time-dependent viscoelastic response occurs, leading to a gradual decrease in passive torque or tension over time (stress relaxation) [8, 9]. Conversely, CTS applies a passive persistent torque to the musculotendinous complex, causing a progressive increase in the joint angle (muscle creep phenomenon) [8, 10]. This approach maintains a higher load on the musculotendinous complex during the same stretch duration compared to that in CAS, potentially leading to a greater reduction in MTS [11–13].

While prolonged stretching impairs athletic performance requiring high-speed power and strength [12, 14, 15], recent reviews suggest that SS of <60 seconds has minimal to no negative impact [16, 17]. Thus, SS within this timeframe for a single muscle group may be suitable for pre-exercise routines. However, research indicates that CAS of <60 seconds does not reduce MTS in the hamstrings [14, 18, 19], presenting a challenge in achieving MTS reduction without compromising performance. Studies show that ≥120 seconds of CAS was needed to increase musculotendinous extensibility in ankle plantar flexors [20], whereas <60 seconds of CTS was required to increase extensibility in both hamstrings and ankle plantar flexors [21–23]. This suggests that CTS may effectively reduce MTS within a short duration of time. Despite these findings, very few studies have directly compared the effects of short-duration CTS and CAS on MTS. Konrad et al. [4] observed similar MTS reductions between 120 seconds (four sets of 30 seconds) CTS and CAS in ankle plantar flexors. On the other hand, Cabido et al. [13] reported a greater reduction with CTS for the hamstrings using the same total duration (120 seconds). Furthermore, Herda et al. [11] investigated the time-course changes in MTS following repeated 30-second CTS and CAS sessions of the hamstrings. Their study showed that CTS resulted in significant MTS reduction after a single 30-second stretch, while no such reduction was observed with CAS even after 8 minutes of stretching. Although this emphasizes the utility of CTS for short-period MTS reduction, the exact difference in the required stretch duration and the magnitude of MTS reduction remain unclear. In particular, a duration of 30 to 120 seconds is frequently utilized in clinical practice [24], and the difference between CTS and CAS at this specific stretch duration should be elucidated for each set.

To demonstrate the difference between CTS and CAS at short stretch duration, the study aimed to compare the time-course changes in the MTS of the ankle plantar flexors following four repeated 30-second CTS and CAS sessions. We hypothesized that CTS would lead to a faster and greater reduction of MTS compared to CAS.

METHODS

Experimental design

A crossover design was employed to investigate the time-course changes in the MTS of ankle plantar flexors following four repeated 30-second CTS and CAS sessions. All participants visited the laboratory three times. During the first visit (familiarization session), participants were familiarized with the experimental protocols and underwent measurement of maximum tolerable passive torque threshold. This threshold defines the stretch intensity for both CTS and CAS and represents the torque value at which participants experienced maximum stretch sensation in the ankle plantar flexors without pain during passive dorsiflexion [3]. Following threshold measurement, participants performed passive dorsiflexion to the measured threshold to ensure that the torque value was maintained and tolerable. The remaining two visits involved either CTS or CAS of the ankle plantar flexors of the dominant leg in a randomized order. The dominant leg was defined as the leg used to kick the ball. Each condition was performed at the same time of the day (±2 hours), with an interval of at least 48 hours. To acclimatize to the laboratory environment (25°C), participants sat quietly for 15 minutes at the beginning of each session. Four sets of 30-second CTS or CAS sessions were performed, separated by 20-second rest intervals. The MTS of the ankle plantar flexors was then measured at each designated time point (Fig. 1).

This study was approved by the local institutional review board (approval number: 18-78). All participants provided written informed consent after receiving a thorough explanation of the study protocol. Study procedures were performed in accordance with the principles of the Declaration of Helsinki.

Fig. 1 around here

Participants

Power analysis using the G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) determined a sample size of 21 participants to detect an interaction effect in the two-way repeated-measures analysis of variance (ANOVA) (effect size=0.25, α=0.05, power=0.8). Twenty-one healthy young males (age: 23.4±2.2 years, height: 173.9±5.3 cm, body mass: 63.6±8.4 kg) volunteered to participate. Exclusion criteria were as follows: current lower limb injury, history of neuromuscular disease, rheumatological diseases, and engagement in regular lower extremity resistance training. Additionally, participants were instructed to refrain from any intensive exercise for 24 hours before each testing session.

Passive ankle dorsiflexion test

A passive ankle dorsiflexion test was conducted until the maximum tolerable torque threshold was reached using a Biodex System 3 isokinetic dynamometer (Biodex Medical System Inc., Shirley, NY, USA). Participants were positioned supine with their knee of the dominant side fully extended to align the lateral malleolus of the fibula with the dynamometer axis. To prevent movement during testing, the foot was securely fastened to the footplate using a Velcro strap, and bilateral thighs and pelvis were stabilized. The neutral ankle joint angle was established as perpendicular to the floor, with positive and negative representing ankle dorsiflexion and plantar flexion, respectively. During maximum tolerable torque threshold measurement, the ankle was dorsiflexed passively from 20° of plantar flexion at 2°/s, and participants pressed the safety trigger button when the threshold sensation was felt [3, 18]. To determine MTS, passive ankle dorsiflexion was performed at pre-stretching and after each set from 20° of plantar flexion up to the angle corresponding to the maximum threshold. Participants performed practice maneuvers twice before pre-stretching measurements and were instructed to relax their lower legs during measurements.

For the MTS calculation, ankle joint angles and torque signals during passive ankle dorsiflexion were output from dynamometer to MyoSystem 1200 (Noraxon USA, Inc., Scottsdale, AZ, USA) and recorded at 1,000 Hz. All signals were processed and analyzed offline using MATLAB software (MathWorks, Natick, MA, USA). Gathered data underwent low-pass filtering at 10 Hz, and gravity correction of the limb was performed using torque data from the starting position [5]. MTS was calculated as the slope of the relationship between passive torque and joint angles using a fitted, second-order, polynomial regression model [24, 25]. Based on previous studies, MTS was calculated every 4° in the final 13° of the final ROM [5]. To capture the overall shape of the torque-angle curve in this study, the average of the four MTS points was used for subsequent analysis. The dorsiflexion angle used for MTS calculation at each measurement time point remained consistent with the maximum ankle dorsiflexion angle during pre-stretching measurement.

CTS and CAS

CTS and CAS were performed using a Biodex dynamometer under the same settings used for the passive ankle dorsiflexion test. The stretching intervention was initiated when reaching maximal dorsiflexion during passive dorsiflexion test. During CTS, the ankle joint was passively dorsiflexed until the maximum tolerable torque threshold was reached. A constant torque load was then maintained to avoid decreases of 2 Nm [4]. For CAS, the joint angles corresponding to the maximum threshold were maintained for each set [12]. As such, both conditions were initiated at the maximum passive torque threshold. Passive torque was maintained during CTS, whereas gradual decrease was observed during CAS. Both protocols consisted of four sets of 30-second stretching duration with 20-second rest intervals between each set. After each 30-second stretch, the lever arm was immediately returned to the starting position.

Statistical analysis

Data are presented as means ± standard deviation. The Shapiro-Wilk test assessed the normality of all data, and two-way repeated-measures ANOVA (condition [CTS and CAS] × time [pre-stretching and four sets]) determined possible interaction effects between condition and time. Relative changes in MTS after stretching were calculated, and a one-way repeated measures ANOVA (condition [CTS and CAS]) was performed. When a significant effect was identified, Bonferroni post-hoc correction was used to compare all parameters. Effect sizes were calculated using partial eta-squared (η^2_p) and *r* values for repeated-measures and between-condition comparisons, respectively. Additionally, 95% mean difference confidence intervals (95% CIs) were calculated. To assess test-retest reliability of MTS, a pilot study was conducted with eight participants who underwent measurements twice one week apart (n = 8). Intra-class correlation coefficients ($ICC_{1,1}$), standard error of measurement (SEM), and coefficient of variation (CV) were calculated based on the pilot data. All statistical analyses were performed using the Statistical Package for the Social Sciences software (version 21.0; IBM Japan Co., Tokyo, Japan), and statistical significance was set at P <0.05

RESULTS

The test-retest reliability

The pilot study demonstrated good reliability for MTS measurement with the following results: $ICC_{1,1}$ of 0.98 (95% CI: 0.93 - 0.99), SEM of 0.04, and CV of 21.4.

MTS

A significant two-way interaction was observed between condition and time (condition × time) for MTS (p=0.03, η_p^2=0.15). Post-hoc analysis revealed significant reductions in MTS for both conditions compared to their pre-stretching values (CTS: p <0.01, CAS: p <0.01). Particularly, MTS measurements after two sets were significantly lower than that in pre-stretching (CTS: p <0.01, CAS: p <0.01) and one set (CTS: p <0.01, CAS: p <0.01). MTS measurements after three sets were significantly lower than that in pre-stretching (CTS: p <0.01, CAS: p <0.01), one set (CTS: p <0.01, CAS: p <0.01), and two sets (CTS: p <0.01, CAS: p <0.01). Lastly, MTS measurements after four sets were significantly lower than that in pre-stretching (CTS: p <0.01, CAS: p <0.01), one set (CTS: p <0.01, CAS: p <0.01), two sets (CTS: p <0.01, CAS: p <0.01), and three sets (CTS: p=0.02, CAS: p <0.01). When comparing both conditions, CTS demonstrated a significantly lower MTS compared to CAS across all sets (p=0.03, p=0.02, p=0.04, and p=0.01, respectively). Conversely, no significant difference in MTS was observed between CTS and CAS at pre-stretching (p=0.17). Furthermore, CTS exhibited a significantly greater relative change in MTS compared to CAS across all sets (p <0.01, p <0.01, p <0.01, and p <0.01, respectively) (Fig. 2).

Table 1 around here

Fig. 2 around here

DISCUSSION

The present study investigated the time-course changes in the MTS of ankle plantar flexors following four repeated 30-second CTS and CAS sessions. Our results showed that both protocols significantly reduced MTS, with further reductions obtained for each set. However, CTS consistently exhibited significantly greater MTS reductions compared to CAS across all sets. These findings suggest that CTS is an effective stretching technique for reducing MTS, even with short durations.

The greater effectiveness of CTS compared to CAS is likely attributed to the opposing mechanisms of each technique. CAS causes stress relaxation during stretching, thereby reducing the passive torque or tension [8, 9]. In contrast, CTS maintains a constant passive torque on the musculotendinous complex, inducing a creep phenomenon that gradually increases the joint angle and strain [8, 10]. This translates to greater mechanical work performed during CTS and consequent MTS reduction for stretch durations of 120–480 seconds, as previously described [11–13]. However, the specific differences in MTS reduction between CTS and CAS during short stretch durations remain unclear. Our findings demonstrated significantly greater reductions in MTS with CTS compared to that in CAS across all sets, highlighting its efficacy even with short stretching durations. CTS can therefore be recommended as the preferable stretching technique for improving flexibility in clinical and athletic settings.

Contrary to our hypothesis, both CTS and CAS significantly reduced MTS after 30 seconds of stretching, with no observed difference in the minimum required stretch duration. Prior research suggests that CAS of <60 seconds did not reduce MTS in the hamstrings or ankle plantar flexors [14, 18, 19, 26, 27]. Moreover, another report indicated that a minimum of 120 seconds was necessary to increase musculotendinous extensibility in the ankle plantar flexors [20]. This discrepancy with our findings may be attributed to the larger stretch angles and higher intensities employed before actual testing. Previous studies on short-duration CAS of the ankle plantar flexors used either 80% of the maximum dorsiflexion angle [27] or an angle with tolerable sensation before discomfort [20]. Our study, on the other hand, defined stretch intensity as the joint angle corresponding to the maximum stretch sensation without pain. Thus, the stretch intensity in this study was potentially higher than that in previous studies. Supporting this notion, Takeuchi et al. [18] reported that high-intensity CAS reduced MTS within 20 seconds. This is consistent with our results showing greater reductions in MTS at 30 seconds with CTS than with CAS. Future studies should explore the minimum stretch duration required for MTS reduction in short-duration exercises (15−20 seconds) [22, 27].

A recent review showed that reduced muscle stiffness from SS may be a contributing factor in preventing muscle injuries [29]. This aligns with the concept that muscles with high stiffness are more susceptible to injury [6]. However, achieving MTS reduction with SS requires prolonged stretch durations that may impact athletic performance [12, 14, 15]. The present study demonstrated that CTS resulted in a greater reduction in stiffness compared CAS, even over a shorter duration. This suggests the potential utility of CTS in warm-up stretching technique to prevent muscle injury.

Despite the valuable insights presented in the study, several limitations must be acknowledged. First, the participants were healthy young males who did not participate in any competitive sports. Caution should be exercised when generalizing the results of this study to patients and athletes in clinical practice. Second, we did not measure athletic performance in this study. As such, we also could not clarify whether short-duration CTS and CAS had a negative impact on athletic performance. Previous reviews have shown that stretch durations of <60 seconds had minimal effects on athletic performance [16, 17]. In addition, Palmer et al. [21] reported no significant changes in maximal voluntary contraction torque following 30 seconds of CTS. Further studies should explore the differences in athletic performance between short-duration CTS and CAS protocols. Third, CTS, which strictly controls passive torque during stretching, is not reproducible without the use of a dynamometer. The results of the present study demonstrate that the creep phenomenon during stretching is effective in reducing musculotendinous stiffness.

CONCLUSION

This study investigated the time-course changes in the MTS of ankle plantar flexors following four repeated 30-second CTS and CAS sessions. Our results showed that CTS resulted in a significantly greater MTS reduction than CAS across all sets. This suggests that CTS may be a valuable stretching technique for warm-up and rehabilitation programs due to its effectiveness in reducing MTS within a short duration.

DECLARATIONS

Funding

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Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical approval

This study was approved by the corresponding institutional review board (approval number: 18-78). All experimental procedures were performed in accordance with the principles of the Declaration of Helsinki.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Data availability statement

The datasets are available upon reasonable request from the corresponding author.

Author contributions

All the authors contributed to the conception and design of this study. Material preparation, data collection, and analysis were performed by K.O. The first draft of the manuscript was written by K.O. and all authors have read and approved the final manuscript.

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Table

Table 1. Musculotendinous stiffness during the passive ankle dorsiflexion test.

	Musculotendinous stiffness (Nm/°)			
	CTS	CAS	95% CI for difference between CTS and CAS	Effect size (*r*) for difference between CTS and CAS
Pre	1.32 ± 0.36	1.33 ± 0.37	− 0.04 to 0.01	0.31
One set	1.27 ± 0.36 [# *]	1.29 ± 0.37 [*]	− 0.05 to − 0.002	0.46
Two sets	1.23 ± 0.35 [# **]	1.26 ± 0.36 [**]	− 0.06 to − 0.01	0.50
Three sets	1.21 ± 0.35 [# ***]	1.25 ± 0.35 [***]	− 0.06 to − 0.002	0.44
Four sets	1.20 ± 0.34 [# ****]	1.23 ± 0.35 [*****]	− 0.05 to − 0.003	0.47

Data are presented as the means±SD. CTS: Constant torque stretching, CAS: Constant angle stretching.
#Significant difference between CTS and CAS.
* MTS in 1 set was significantly lower than that in Pre-stretching.
** MTS in 2 set was significantly lower than that in Pre-stretching and one set.
*** MTS in 3 set was significantly lower than that in Pre-stretching, one set, and two sets.
*** MTS in 4 set was significantly lower than that in Pre-stretching, one set, two sets, and three sets.

Figure captions

Fig. 1 Experimental design.

CTS: constant torque stretching, CAS: constant angle stretching, MTS: musculotendinous stiffness.

Fig. 2 Relative changes in musculotendinous stiffness after stretching.

Data are presented as means±SD.
CTS: constant torque stretching, CAS: constant angle stretching.

Significant difference between CTS and CAS.

Fig. 1

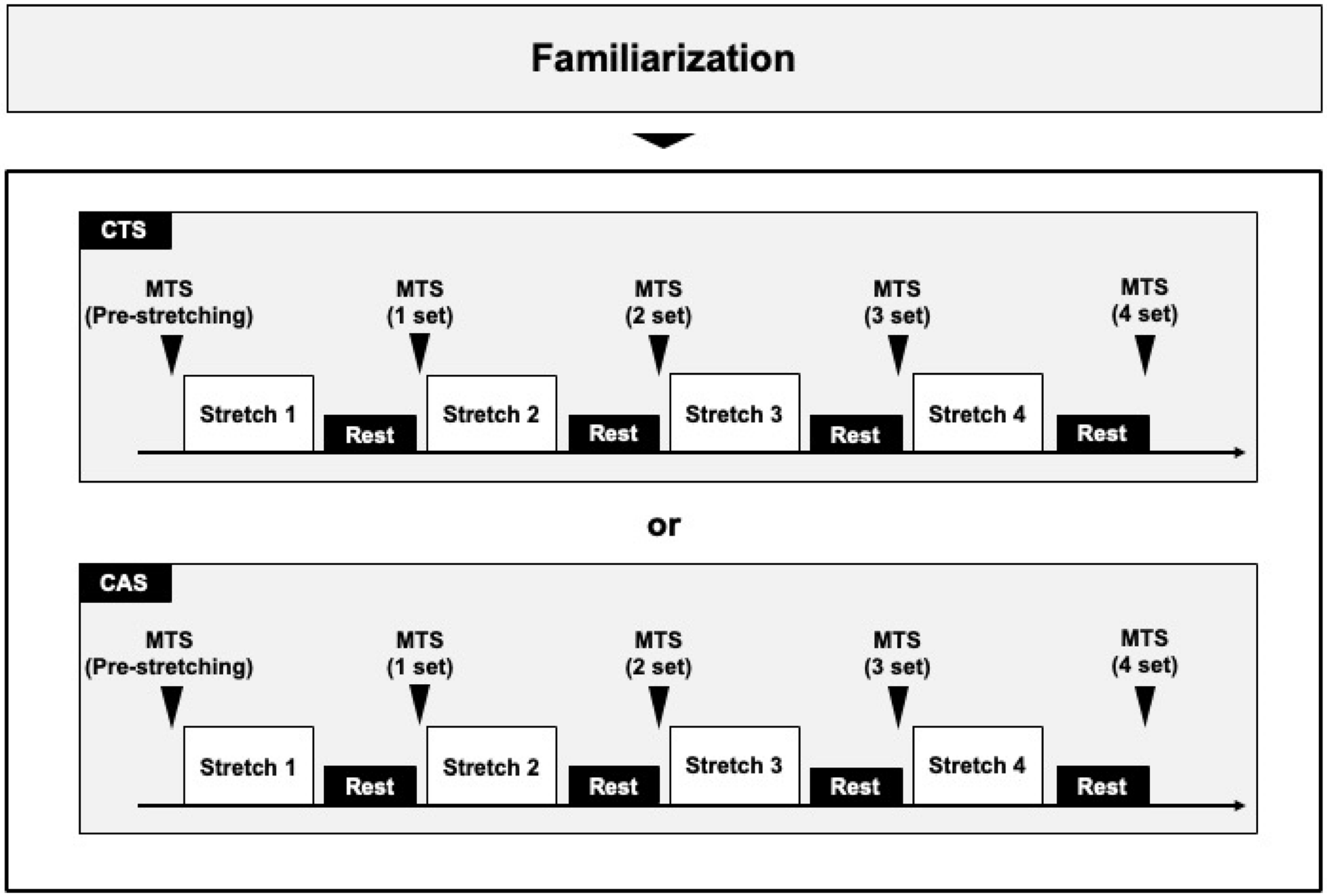
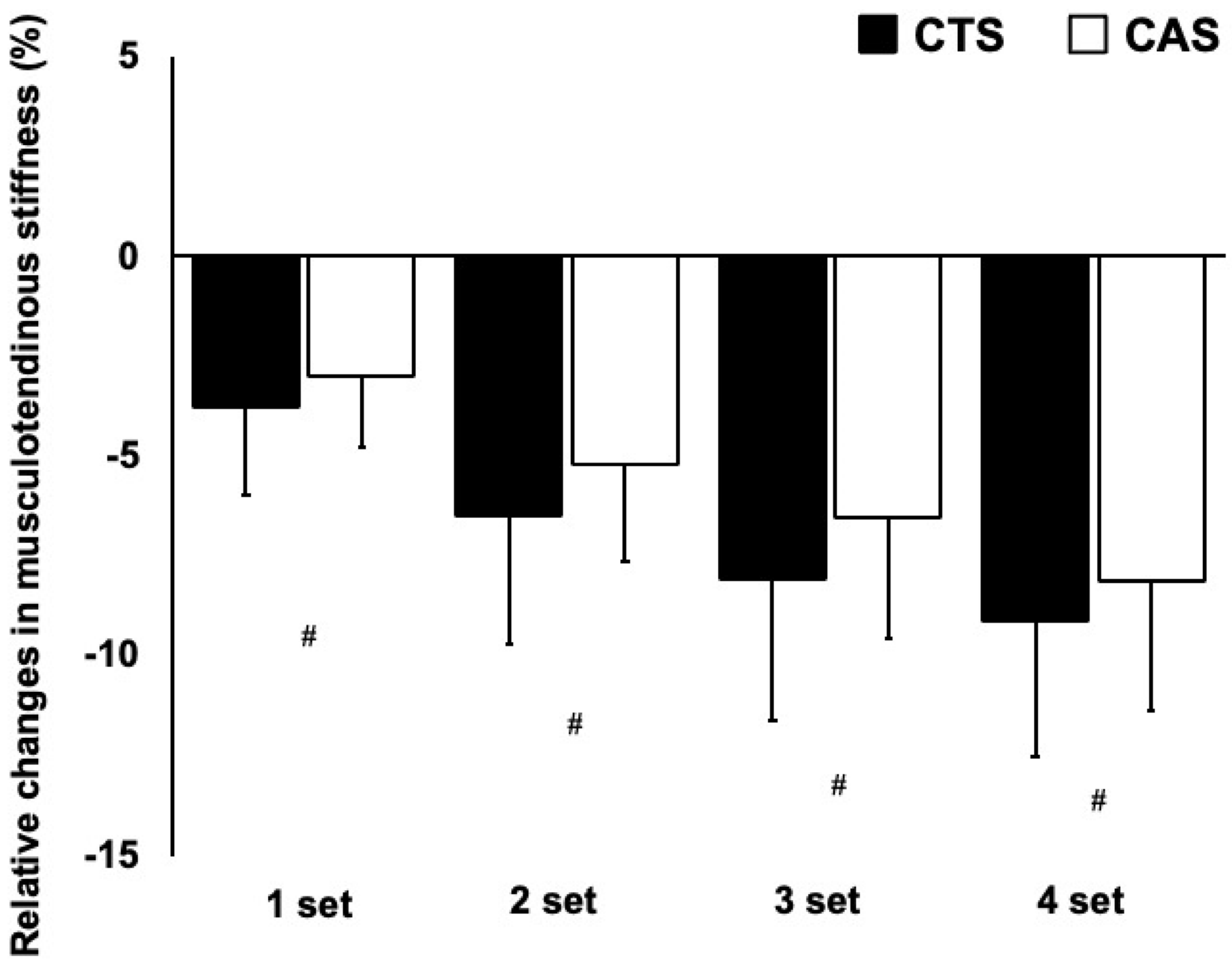

Familiarization
CTS
MTS
(Pre-stretching)
MTS
(1 set)
MTS
(2 set)
MTS
(3 set)
MTS
(4 set)
Stretch 1
Rest
Stretch 2
Rest
Stretch 3
Rest
Stretch 4
Rest
or
CAS
MTS
(Pre-stretching)
MTS
(1 set)
MTS
(2 set)
MTS
(3 set)
MTS
(4 set)
Stretch 1
Rest
Stretch 2
Rest
Stretch 3
Rest
Stretch 4
Rest

Fig. 2


CTS
CAS
Relative changes in musculotendinous stiffness (%)
5
0
-5
-10
-15
#
#
#
#
1 set
2 set
3 set
4 set