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ORIGINAL ARTICLE

Muscle and joint responses during and after static stretching performed at different intensities

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Abstract
Purpose We investigated the effects of plantarflexor static stretching of different intensities on the medial gastrocnemius (GAS) shear elastic modulus, GAS fascicle length and ankle passive torque–angle responses during and after stretching.
Methods Participants performed three stretching sessions of different intensities: 40 % (R40) of maximal dorsiflexion range of motion (ROM), 60 % (R60) of ROM, and 80 % (R80) of ROM. Each stretching lasted 10 min. The GAS architecture, GAS shear elastic modulus, ankle passive torque–angle, and muscle activity were assessed before, during, and after the stretching.
Results The absolute and relative (i.e., normalized to the static stretching start value) GAS shear elastic modulus relaxation varied across stretching intensities. The absolute passive torque relaxation varied across intensities ($p < 0.05$) but not when normalized to the stretching start value. No significant changes were observed in GAS fascicle length during the stretching ($p = 0.93$). After stretching, passive torque at a given angle was significantly decreased for R60 [-0.99 ± 0.59 Nm (-6.5 ± 3.8 %), $p < 0.001$] and R80 [-1.05 ± 1.12 Nm (-6.8 ± 6.3 %), $p = 0.004$], and GAS shear elastic modulus decreased only for the R80 [-9.3 ± 7.2 kPa (-14.1 %), $p = 0.003$]. No significant correlations were found between the magnitude of relaxation during stretching and post-stretching effect in the GAS shear elastic modulus or ankle passive torque variables. No significant relation was found between the shear elastic modulus and the ankle passive torque responses during and after stretching.
Conclusion The effects of stretching on joint passive torque do not reflect changes in the medial gastrocnemius shear elastic modulus, and these responses to stretching depend on its intensity.

Keywords Elastography · Supersonic shear imaging · Fascicle length · Ultrasound · Passive torque · Relaxation · Gastrocnemius

Abbreviations

CI	Confident interval
EMG	Electromiography
GAS	Gastrocnemius medialis
ICC	Intraclass correlation coeficient
MTJ	Muscle-tendon junction
r	Pearson correlation coeficient
R40	40 % of maximal dorsiflexion range of motion
R60	60 % of maximal dorsiflexion range of motion
R80	80 % of maximal dorsiflexion range of motion
ROM	Range of motion
SEM	Standard error of measurement
SSI	Supersonic shear imaging

Introduction

Numerous studies have shown that static stretching acutely increases the maximal joint range of motion

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(ROM), and decreases the passive torque developed by the musculo-articular complex in resistance to the motion (Gajdosik 2001; Magnusson et al. 1996; McHugh et al. 1992). Some of these studies have analyzed passive torque relaxation during static stretching (Magnusson et al. 1995; McHugh et al. 1992; Tian et al. 2010), while others analyzed the changes in passive torque immediately after the stretching protocol (Magnusson et al. 1996; Morse et al. 2008). Thus, it is implicit that passive torque relaxation leads to a passive torque decrease at a given joint angle after stretching; however, the relationship between the passive torque relaxation and the stretching effects observed after the protocol might be more complex. It remains unknown whether the magnitude of passive torque decrease that is noticed after stretching is related to the degree of passive torque relaxation.

In addition, few studies have investigated the effects during and after static stretching of different intensities. The results of Tian et al. (2010) indicate that the passive torque relaxation during stretching increases with stretching intensity, while the relative passive torque relaxation (i.e., expressed in percentage of the maximal passive torque reached) at the ankle is poorly affected by the knee and ankle angles; and consequently the muscle length. The authors suggested two hypotheses to explain this result: (1) the relaxation is mainly due to single-joint structures, or (2) relaxation is independent of the gastrocnemius length. If the second hypothesis is valid, then this could have very interesting applications for biomechanical modeling (Tian et al. 2010). Since passive torque measurement represents the total resistance of the global joint muscle-articular complex to motion, and involves several anatomic structures crossing the joint (e.g., muscle–tendon, skin, nerve), more localized measurements performed on the gastrocnemius could be used to test this second hypothesis.

For that purpose, it was recently shown that supersonic shear imaging (SSI) elastography can provide an estimation of changes in localized passive tension in one muscle (Maïsetti et al. 2012; Koo et al. 2013). In respect to the effects of acute stretching on resting muscle shear elastic modulus using SSI, a previous study reported a decrease in muscle resting shear elastic modulus after static stretching (Akagi and Takahashi 2013). However, the probe was placed transversely during the measurements, but longitudinal measurements correlate better with the muscle passive tension (Gennisson et al. 2010; Koo et al. 2013). More recently, Nakamura et al. (2014) reported a decrease in muscle longitudinal shear elastic modulus after 120 s of static stretching; however, the effect of stretching intensity was not analyzed in their study.

Another unanswered question relies upon the structural factors underlying the passive torque relaxation and the stretching effects. The conclusions of previous studies using ultrasound to examine the post-stretch effects on muscle and tendon have not reached a consensus (Herda et al. 2011; Kato et al. 2010; Kay and Blazevich 2009; Kubo et al. 2002; Morse et al. 2008). For instance, tendon stiffness is reported to be decreased (Kato et al. 2010) or not affected (Kay and Blazevich 2009; Kubo et al. 2002; Morse et al. 2008); while muscle stiffness is stated to decrease (Kay and Blazevich 2009; Morse et al. 2008), or not be affected (Kato et al. 2010). On the other hand, we are aware of only one recent study that performed muscle and tendon length measurements during passive stretching (Nakamura et al. 2013). This study reported an increase in muscle length during the passive torque relaxation using ultrasound measurements performed on the myotendinous junction (MTJ) of the gastrocnemius, indicating that the tendon is shortened and thus the relaxation would be more due to muscle than tendinous structures. Considering that tendon contributes to about 70 % of the change in length of the gastrocnemius muscle tendon unit during passive stretching (Herbert et al. 2011), this result could be surprising and needs to be confirmed with more direct measurements of muscle fascicle length.

To provide a better understanding of static stretching protocols, the objective of the present study was to analyze both relaxation during static stretching and the acute effects immediately after the protocol using passive torque, elastographic and ultrasound measurements. Thus, this study was designed (1) to observe whether the size of the stretching effects on joint torque and muscle shear elastic modulus is related to the magnitude of relaxation, (2) to assess the effects of different stretching intensities on joint and muscle properties, and (3) to compare both acute effects of stretching and relaxation in one muscle–tendon (i.e., changes in passive muscle tension estimated using elastography and fascicle length using ultrasound) to the whole muscle-articular system (i.e., changes in passive torque). Since the different relaxation trials were performed on different days, the preliminary step was to determine the inter-day reliability of shear elastic modulus and sonographic measurements during passive stretching.

Methods

Participants

Ten healthy volunteers (all men; age: 27.5 ± 1.4 years; height: 1.80 ± 0.05 m; body mass: 73.9 ± 5.8 kg) came to the laboratory on three consecutive days. The study was approved by the local Ethics Council.

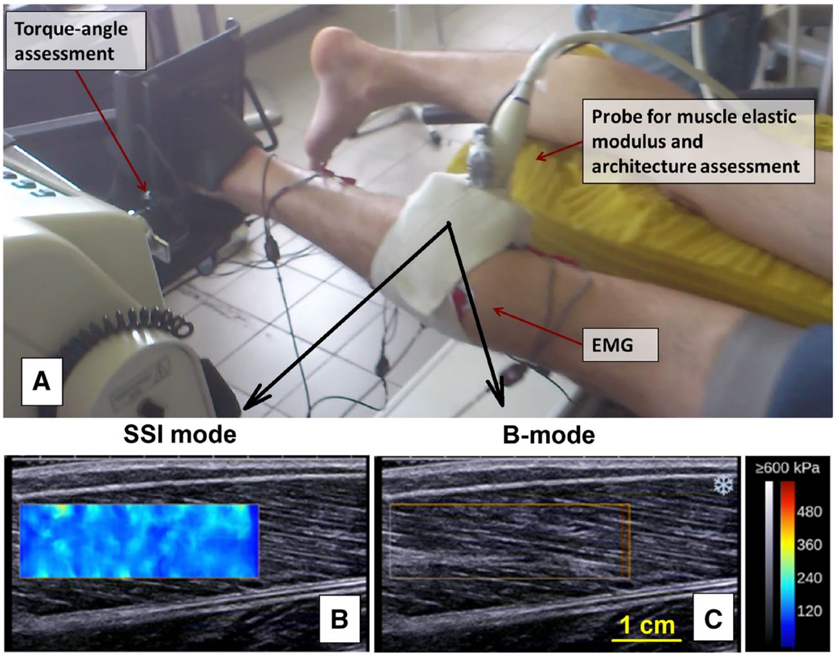

Fig. 1 **a** Experimental setup for stretching the ankle plantarflexors and to assess the ankle passive torque–angle and muscle activites using EMG, **b** medial gastrocnemius shear elastic modulus using supersonic shear imaging elastography mode, **c** fascicles length using ultrasonography in B-mode

Equipment

Passive torque–angle

An isokinetic dynamometer (Biodex 3 medical, Shirley, NY, USA) was used to impose passive ankle dorsiflexion and to measure (1,000 Hz) ankle angle and torque (Fig. 1). The lateral malleolus was aligned with the axis of the Biodex dynamometer. The perpendicular position between the foot and leg was considered the neutral position (i.e., 0°). Ankle torque–angle data was recorded at a sampling rate of 1 kHz (MP36, BIOPAC, Goleta, California, USA).

Muscle shear wave elastic modulus (elastography) and fascicle length

An Aixplorer ultrasound scanner (version 7.0; Supersonic Imagine, Aix-en-Provence, France) and a linear transducer array (4–15 MHz, Super Linear 15-4, Vermon, Tours, France) were used simultaneously in shear wave elastography mode (musculo-skeletal preset) to assess medial gastrocnemius shear elastic modulus (Bercoff et al. 2004), and in B-mode to assess the muscle architecture (Fig. 1a, b). The transducer was held statically with a custom-made cast placed on the skin according the orientation of the muscle fascicles (Fig. 1b). Assuming a linear elastic behavior (Bercoff et al. 2004), the muscle shear elastic modulus (μ) was calculated as follows (1):

$$\mu = \rho V_{\mathrm{s}}^{2} \tag{1}$$

where ρ is the density of soft tissues (1,000 kgm^3) and V_{s} is the shear wave speed. The probe was positioned over the gastrocnemius muscle mid-belly by an experienced examiner. The maps of the shear elastic modulus were collected at 1 Hz with a spatial resolution of 1×1 mm. The timing of each shear elastic modulus measurement was determined using the signal from a microphone (MB Quart K800, frequency response: 40–18,000 Hz, sensitivity: 16.25 mV/Pa) recorded using the same device as that which was used for torque and angle (MP36, BIOPAC, Goleta, California, USA). The maximal duration of each sonogram video was ≈2 min and 40 s due to equipment recordings limitation. Thus, about 15 s of recording were missing three times during the 10 min static stretching protocol for each participant.

Electromyography

To ensure a passive condition during stretching maneuvers, two conductive adhesive hydrogel surface electromyography (EMG) electrodes (Kendall™ 100 Series Foam Electrodes, Covidien, Massachusetts, USA) with an inter-electrode distance of 20 mm (center-to-center) were placed over the gastrocnemius medialis (GAS), gastrocnemius lateralis, soleus, and tibialis anterior. The electrodes were placed according to the surface EMG for non-invasive assessment of muscles guidelines (SENIAM), except for the GAS muscle. Due to the probe positioning, the electrodes for this muscle were placed at the most proximal site of the muscle mid-belly. Before applying the electrodes, skin was shaved and cleaned with alcohol to minimize impedance. Raw EMG signals were amplified close to the electrodes (gain 375, bandwidth 8–500 Hz) and digitized at a sampling rate of 1 kHz (ME6000, Mega Electronics Ltd., Kuopio, Finland). An examiner regularly monitored EMG during all trials. A trigger was used to synchronize torque–angle and EMG measurements.

Protocol

Three 10-min static stretching sessions at different stretch intensities were performed on three different days in a random and balanced order. For each session, upon arrival of participants to the laboratory, skin was prepared for EMG, and participants were laid prone with the knee fully extended. Participants were firmly strapped to the ergometer to ensure that the body was not moved during the passive dorsiflexion tests. Maximal dorsiflexion passive ROM was determined in the first session by manually moving the platform fixed to the foot. Then, four dorsiflexion-to-plantarflexion cycles (from −40° in plantar flexion position to 80 % of maximal dorsiflexion ROM) at 5°/s were performed for tissue conditioning, followed by a fifth cycle at 2°/s to assess the inter-day reliability of measurements, and for comparison to a cycle performed post stretching. Next, three rapid stretches were performed at 100°/s to test habituation, and EMG was visually inspected in real time to ensure that no significant muscle activity would occur during the stretching maneuver. A 10-min static stretching was then imposed 30 s later by displacing the ankle at 100°/s from the −40° plantar flexion position to the target dorsiflexion position. A 100º/s velocity was used because, according to the quasi-linear viscoelastic theory, the amount of relaxation should be measured when using a step loading; and thus we have used the maximal velocity possible without evoking considerable EMG activity, in accordance to the protocol used by Tian et al. (2010). Depending on the session, the target dorsiflexion position was set at 40, 60 and 80 % of the previously determined maximal ROM (R40, R60 and R80). 30 s after the stretching, four cycles were performed at 5°/s and a fifth cycle at 2°/s to determine the post-stretching effects. The examiner carefully checked that the heel did not move from the foot platform in all stretching tests. In the end of the session, three maximal voluntary plantarflexor isometric contractions were performed to normalize the EMG values.

Data processing

The passive torque was gravity-corrected by subtracting the torque of the footplate to the recorded torque. The SSI recordings were exported from software (Version 7.0, Supersonic Imagine, Aix en Provence, France) in mp4 video format and sequenced in jpeg image files. All subsequent processing was performed using standardized Matlab scripts (Matlab, Mathworks). Image processing converted the colored map into shear elastic modulus values. For each image, the average value of shear elastic modulus was calculated over a region of interest corresponding to the largest muscular region for the GAS (Fig. 1b, size ≈400 mm^2).

For fascicle length calculation during relaxation, the manual digitizing was performed using a classic extrapolation method (Noorkoiv et al. 2010). All sonographic images were processed using ImageJ software (NIH, 1.47v, USA). Three examiners digitized two images of each stretching trial: one 3 s after achieving the static stretching position, and the other at the end of the relaxation period. The images were masked so that the examiners could not identify whether they had been obtained at the beginning or end of relaxation. Examiners were instructed to track the same fascicle in the two images by doing a print screen of the first image tracked, determining the coordinates of the first track, and using the coordinates to identify the same fascicle on the second image. It should be noted that the probe was fixed to the skin and it was unchanged during all the data collection; thus there was no changes in fascicles location on the sonogram images. In all measurements, fascicle length (FL) was calculated using the equation: $\mathrm{FL} = L + (h/\sin\beta)$, where L is the observable fascicle length from the deep aponeurosis toward superficially to the most visible end-point, h is the distance between the superficial aponeurosis and the fascicle's visible distal end-point, and β is the angle between the fascicle and the superficial aponeurosis. For the pre and post fascicle length measurements, the automatic tracking routine proposed by Cronin et al. (2011) was used. This routine automatically tracks the coordinates of the fascicle identified on the sonogram, based on the Lucas–Kanade optical flow algorithm with an affine optic flow extension (Cronin et al. 2011). To ensure that the same fascicle was being measured between the pre and post cycles, the sonogram image of the fascicle tracked in the first video was saved so that examiner could subsequently draw the fascicle at the same location.

Relaxation was calculated for torque, shear elastic modulus, and fascicle length by subtracting the average value of the five last seconds at the end of the 10-min static stretch from the value 3 s after the peak torque (Tian et al. 2010). The initial 3 s of the relaxation were removed in order to account for the finite velocity during the stretch, since according to the quasi-linear viscoelastic theory the stretch should be applied in a step protocol in order to measure the actual amount of relaxation (Tian et al. 2010). Similar procedures to Nordez et al. (2009) were followed for processing the EMG signals. The root mean square of electromyographic signals (RMS-EMG, calculated over 300 ms windows) was also calculated for each second and normalized to the maximal voluntary plantarflexor isometric contraction.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 19.0 (IBM Corporation, New York, USA). Normal distribution was checked for all data variables using Shapiro–wilk test. Inter-day reliability was determined by comparing the pre-conditioning cycle at 2°/s using intraclass coefficient correlation (ICC) at a 95 % confident interval (CI) and standard error of measurement (SEM) (Hopkins 2000) for fascicle length, passive torque and SSI measurements at 75 % of maximal dorsiflexion ROM. The fascicle length tracking repeatability (i.e., processing two successive pre-stretching cycles for each participant) was determined using the ICC and SEM.

For the relaxation analysis, two-way ANOVAs [protocol (R40, R60, R80) × time (start, end)] were performed for each variable (passive torque, shear elastic modulus, fascicle length). Then, one-way ANOVAs [protocol (R40, R60, R80)] were performed on absolute and relative (i.e., normalized to the maximum value obtained at the start of static stretching) relaxation values for each variable. When a significant interaction was found between factors, Bonferroni's post hoc comparisons tests were performed to detect individual differences.

For the analysis of stretching effects, two-way repeated measures ANOVAs [protocol (R40, R60, R80) × time (pre, post)] were performed for passive torque, shear elastic modulus and fascicle length at 0, 65, 70, and 75 % of dorsiflexion maximal ROM, and for average EMG during the ankle cycles. When a significant effect was observed, post hoc Bonferroni analysis was performed.

Pearson correlation coefficients (r) were used to determine the relation between the passive torque and shear elastic modulus response both during and after the stretching, and to determine the relation between the size of stretching pre-to-post effects and relaxation magnitude response on joint torque and muscle shear elastic modulus. Statistical significance was set to $p < 0.05$.

Results

EMG

All muscles' EMG were below 1 % of MVC during the measurements

Reliability

The inter-day reliability was good for both shear elastic modulus [ICC = 0.68 (0.36–0.88), SEM = 14.8 kPa], and passive torque [ICC = 0.95 (0.89–0.98), SEM = 1.1 Nm]. A high fascicle tracking repeatability [ICC = 0.96 (0.87–0.99), SEM = 0.3 mm] and a moderate inter-day reliability were observed [ICC = 0.50 (0.12–0.79), SEM = 1.0 mm].

Passive torque vs. shear elastic modulus

No significant correlations were observed between the relative changes between passive torque and shear elastic modulus during relaxation (R40: $r = -0.21$, $p = 0.56$; R60: $r = 0.12$, $p = 0.74$; R80: $r = -0.21$, $p = 0.56$; all intensities: $r = -0.13$, $p = 0.72$) and after the stretching (R40: $r = 0.04$, $p = 0.91$; R60: $r = -0.09$, $p = 0.80$; R80: $r = 0.18$, $p = 0.62$; all intensities: $r = 0.16$, $p = 0.66$).

Relaxation vs. stretching effects

No significant correlation was observed between the relative changes in passive torque obtained during (i.e., relaxation) and after static stretching (i.e., post stretching effects) for R40 ($r = -0.24$, $p = 0.51$), R60 ($r = 0.19$, $p = 0.61$), and R80 ($r = 0.26$, $p = 0.47$). The same results were obtained for the shear elastic modulus (R40: $r = 0.41$, $p = 0.24$; R60: $r = 0.09$, $p = 0.81$; and R80: $r = 0.15$, $p = 0.67$).

Relaxation

For all participants, the average values of passive torque and muscle shear elastic modulus relaxation during stretching at the three different ankle angles are shown in Fig. 2.

Concerning the absolute values at the start and end of static stretching, a main effect of time was found for passive torque ($p < 0.001$) and shear elastic modulus ($p < 0.001$), while this was not the case for fascicle length ($p = 0.12$). In addition, significant protocols × time interactions were found for both the passive torque ($p = 0.014$) and shear elastic modulus ($p < 0.001$), while this was not significant for fascicle length ($p = 0.93$). Passive torque was decreased at the end of the static stretching in all protocols (R80 = −7.0 ± 5.2 Nm, $p = 0.002$; R60 = −3.4 ± 1.8 Nm, $p < 0.001$; and R40 = −2.1 ± 0.8 Nm, $p < 0.001$). For SSI measurements, shear elastic modulus significantly decreased at the end of the relaxation period for both R80 (−19.1 ± 9.1 kPa, $p < 0.001$) and R60 (−6.8 ± 4.9 kPa, $p = 0.002$), but not for R40 (−1.3 ± 1.8 kPa, $p = 0.06$).

Regarding the absolute relaxation (i.e., total decrease during the static stretching), the main effects of protocol were found for both torque ($p = 0.003$, Fig. 3a) and shear elastic modulus ($p < 0.001$, Fig. 3b), but not for fascicle length ($p = 0.372$, Fig. 3c). Concerning relative relaxation, the main effects of protocols were found for the shear elastic modulus ($p < 0.001$, Fig. 3b), but not for passive torque ($p = 0.444$, Fig. 3a) or fascicle length ($p = 0.439$, Fig. 3c).

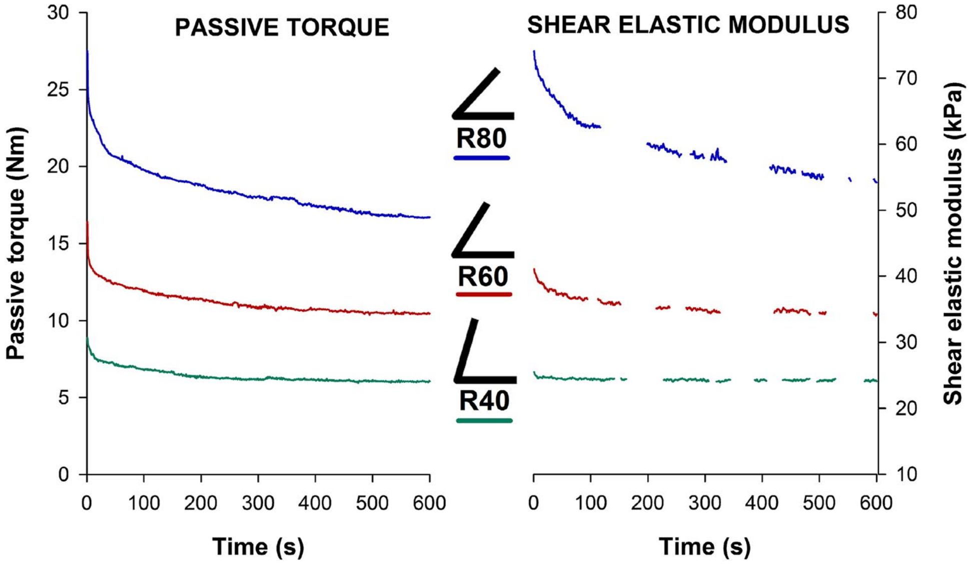

Fig. 2 Average values for all participants of ankle passive torque (*left*) and shear elastic elastic modulus (*right*) relaxation during a 10-min static stretch at three different intensities R80—Stretch at 80 % of maximal range of motion (ROM); R60—Stretch at 60 % of ROM; R40—Stretch at 40 % of ROM. Note: Due to SSI recording timing limitation, the average shear elastic modulus values presented are interrupted. Large timing are shown on this figure due to the averaging across participants

Stretching effects

The average values of the shear elastic modulus and passive torque responses for all participants before and after the three different stretching protocols are depicted in Fig. 4. For the passive torque, a significant main effect was observed for: time at 65 % ($p = 0.01$), 70 % ($p = 0.0001$), and 75 % of maximal ROM ($p = 0.02$); protocol at 70 % of ROM ($p = 0.03$); and, protocol × time at 70 % of ROM ($p = 0.03$). No effect was found for shear elastic modulus at rest, 65 or 70 % of maximal ROM, but a significant effect was observed at 75 % of ROM for protocol × time ($p = 0.04$), protocol (0.03), and time ($p = 0.04$).

For the four angles tested, no significant effect was observed for protocol ($p = 0.23$–0.24), time ($p = 0.31$–0.67), or protocol × time ($p = 0.23$–0.59) on the fascicle length after stretching.

Discussion

Joint torque–angle, muscle shear elastic modulus, and muscle fascicle length were assessed in vivo before, during (i.e. relaxation), and after three stretching protocols with different stretching intensities (i.e. three different ankle angles). Despite the small sample size used, it was observed a statistical power higher than 0.8 in most of the variables. A low EMG signal (<1 % of maximal contraction) was observed during stretching for all participants; thus, we assume that this slight activity did not affect the measurements (Gajdosik 2006). In respect to the reliability assessment, we found acceptable results for all variables; the good shear elastic modulus inter-day reliability enabled us to compare changes across sessions, and the high fascicle repeatability allowed to perform comparisons within a session. The main findings of this study were: (1) the magnitude of stretching effects was unrelated to the size of relaxation for both torque and shear elastic modulus; (2) the joint torque response during and after the stretching did not reflect the changes in shear elastic modulus; (3) both absolute and relative changes of muscle shear elastic modulus during and after stretching varied across different stretching intensities; and (4) fascicle length did not change during static stretching.

Previous studies have assumed that the degree of the stretching effects on joint passive torque and stiffness depends on the size of the relaxation that occurs during the static stretching (Cabido et al. 2014; Herda et al. 2011). Consequently, a higher stretching duration and intensity has been advocated to increase the magnitude of the stretching effects as a consequence of a higher torque relaxation. However, the results of the present study did not show any significant correlation between the magnitude of the stretching effects and the size of relaxation in both muscle shear elastic modulus and joint passive torque. A similar conclusion was reached after reanalyzing the passive torque data obtained on 47 subjects in a recent study targeting the knee flexors (data not published, Freitas et al. in press). This indicates that other factors than the amount of relaxation, not examined in the present study, likely influence the magnitude of stretching effects. For example, the relaxation may depend of the degree of the muscle lengthening (Freitas et al. in press). In addition, the lack of significant correlation between the amount of relaxation for shear elastic modulus and passive torque may be explained by the fact that the comparison was performed between a localized shear elastic modulus measurement in one muscle, with a global joint passive torque measurement produced by

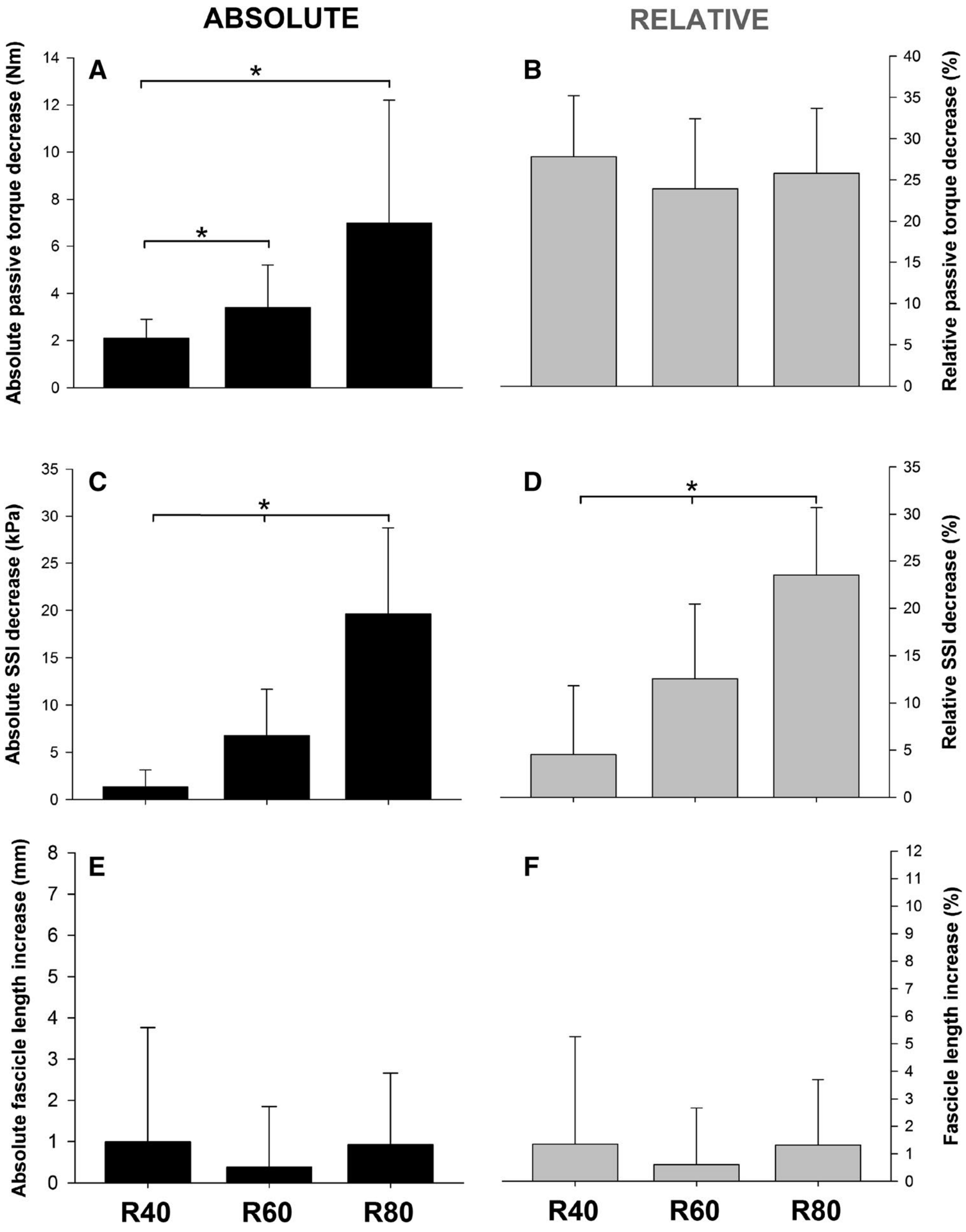

Fig. 3 Absolute and relative (normalized to peak value) of stress relaxation for (**a** and **b**) passive torque and (**c** and **d**) shear elastic modulus, and (**e** and **f**) fascicle length change. *Statistical different between protocols at $p < 0.05$

several muscles. Thus, it is possible that stretching effects are not homogeneous among the muscles involved. Future studies should examine this.

Regarding the relaxation phenomenon, it is often assumed that muscle relaxation occurs at a length beyond the slack length (Abbott and Lowy 1956). It is also reported that when the muscle in vitro is stretched slightly above the slack length, the stress decreases close to the resting values; also, when the stretch is higher, the stress decay does not fall to resting values (Abbott and Lowy 1956). In the present study, we have stretched the plantar flexors muscles at three ankle angles corresponding to 17.1 ± 4.4° (R40), 25.7 ± 6.6° (R60), and 34.3 ± 8.7° (R80) of dorsiflexion; whereas the GAS assume a length above the slack length (i.e., GAS detaches the slack length in an ankle angle of 24.3 ± 5.8° of plantarflexion; Hug et al. 2013). We only observed a decrease in shear elastic modulus for the two highest intensities (R60 and R80), and not for R40. It is possible that the muscle relaxation in vivo has a pattern response different from an in vitro condition, because muscle tissue is surrounded by connective tissue and thus a force transmission may occur between these two tissues. This should be confirmed in a future study since it has implications for biomechanical modeling and exercise interventions.

Another interesting finding was that both absolute and relative muscle passive tension relaxation estimated using SSI was shown to be dependent upon muscle length. As in

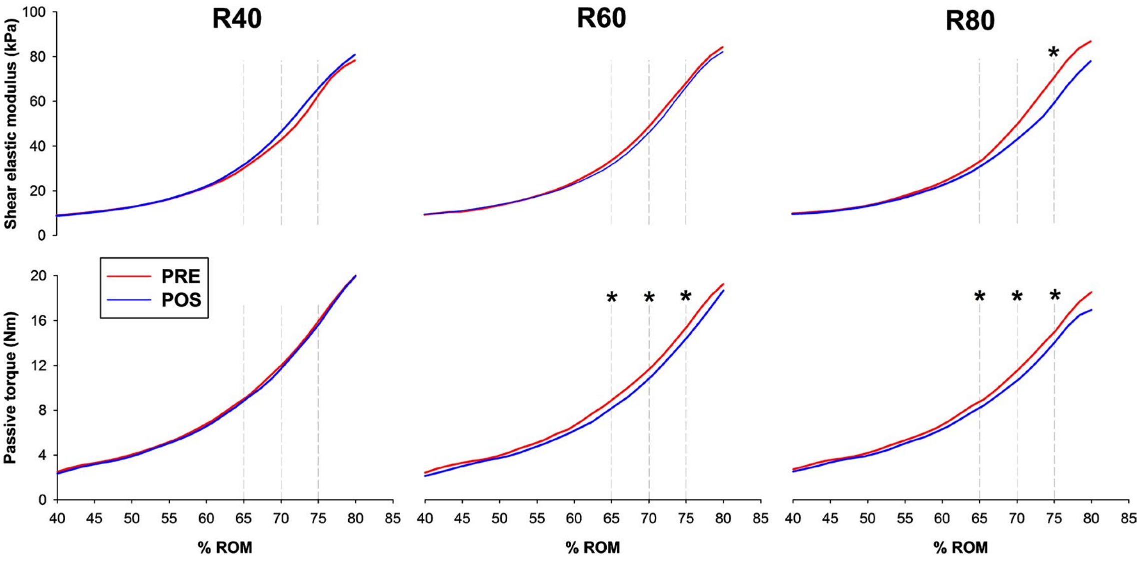

Fig. 4 Average response of shear elastic modulus and passive torque before and after the stretching intervention for the different intensities. The *grey lines* indicate the passive torque and shear elastic modulus at three distinct angles for the three static stretching protocols. *Statistical different between pre and post measurements ($p < 0.05$). ROM—maximal range of motion (ROM); R40—40 % of ROM; R60—60 % of ROM; R80—80 % of ROM

the present study, Tian et al. (2010) showed that relative torque relaxation at the ankle was minimally affected by changing gastrocnemius muscle–tendon unit length. Based on this result, we initially hypothesized that relaxation of the GAS would be minimally affected by its length. However, the results of the present study contradict this hypothesis, since the GAS shear elastic modulus relaxation was higher as long the stretching intensity increased. This suggests that the ankle passive torque measurement cannot be used to infer to the GAS passive tension (i.e. shear elastic modulus). Interactions between mono- and bi-articular structures crossing the joints (Bojsen-Møller et al. 2010; Tian et al. 2012) may explain the different relative relaxations. Thus, it is suggested that muscle effects to stretching should examined with more direct measures instead of joint passive torque assessments.

Also, we unexpectedly observed that the magnitude of torque relaxation was not related to the GAS shear elastic modulus relaxation. This suggest that the contribution of GAS relaxation is not proportional to the ankle torque relaxation, which in turn indicates that other plantarflexor muscles (e.g., soleus) might have different relaxation responses. In addition, regarding the factors underlying muscle tension and joint torque relaxation, Nakamura et al. (2013) observed a MTJ displacement of ~4.5 mm during a 5-min static stretching, and thus suggesting a muscle lengthening during the static stretch. Based on these results, we would expect to observe an increase of about 4.7 mm in fascicle length in the current study (i.e., considering the average of 18° pennation angle and a fascicle length of 69 mm observed in our study). However, no significant changes in fascicle length were observed during the 10-min static stretch. One possible reason for these different results might be the independent motion of aponeurosis in respect to the muscle–tendon junction. Another reason could be related to the different methodological procedures used in our study and Nakamura's (i.e., blinded condition). Because changes of about 4 mm should be visible when visually comparing pre and post images, and because no motion was observed in our ultrasound images, the present study suggests that the relaxation does not cause changes in fascicle length during the stretch. Thus, other factors should be examined to explain muscle relaxation during static stretching.

Regarding the immediate effects on muscle passive stiffness after static stretching, previous studies have suggested a decrease based on passive torque measurements, assuming that passive torque represents muscle passive tension (Gajdosik 2001; Magnusson et al. 1996; McHugh and Cosgrave 2010; Mizuno et al. 2013). However, the stretching effects in one muscle have never been investigated in vivo at different stretching intensities using a more direct measurement (i.e. elastography). While in some conditions, the ankle torque and GAS shear elastic modulus showed similar results (no change for the R40 protocol, and decreases for the R80), for the R60 protocol, the passive torque decreased while shear elastic modulus was unchanged. Moreover, changes in passive torque were not significantly related to changes in GAS shear elastic modulus. This suggests that the passive torque response does not reflect changes in the muscle passive tension of one muscle crossing the joint. Therefore, we hypothesize that the stretching effects may vary among muscles crossing the same joint. A future study should examine this hypothesis. The present results also suggest that absolute effects on both joint passive torque and muscle passive tension induced by static stretching are dependent upon the stretching intensity. The muscle passive tension only significantly decreased after stretching in the R80 condition. Therefore, this finding do not support the studies that suggest a low stretching intensity for a higher passive torque decrease (Light et al. 1984; Usuba et al. 2007). The passive torque decrease was higher for R80 than for R40, with no significant differences between R40 and R60. It has been suggested that longer stretching duration induces higher torque decrease (Freitas et al. in press); however, the stretching intensity should also play a role in joint torque and muscle tension acute decrements. Thus, it is possible that the stretching effects should be potentiated at certain intensity threshold; this issue should be examined in a future study. The effects of static stretching on the passive properties of muscle and tendon is a topic still debatable in the literature, whereas different results have been reported by previous studies (Herda et al. 2011; Kato et al. 2010; Kay and Blazevich 2009; Kubo et al. 2002; Morse et al. 2008). For instance, the tendon stiffness was reported to be decreased (Kato et al. 2010) or unaffected (Kay and Blazevich 2009; Kubo et al. 2002; Morse et al. 2008). Muscle stiffness was found to decrease (Kay and Blazevich 2009; Morse et al. 2008) or remain unaffected (Kato et al. 2010). Muscle–tendon unit stiffness was reported to decrease (Morse et al. 2008) or not change (Herda et al. 2011). However, it should be kept in mind that the muscle stiffness measurements were performed using torque–angle assessments, under certain assumptions that have not been confirmed. For instance, Kay and Blazevich (2009) calculated muscle stiffness through the relation between the muscle fascicle length and the joint passive torque assuming that the joint torque would reflect the muscle passive tension. Also, Kato et al. (2010) calculated muscle stiffness as muscle fascicle length divided by the muscle–tendon unit length, which is known as deformation (Baumgart 2000). However, the stiffness measurement implies that length and passive tension from the tissue is known (Baumgart 2000). In the present study, the GAS passive tension was assessed in vivo by measuring the shear elastic modulus using supersonic shear wave elastography (i.e., shear elastic modulus is linearly related to changes in passive muscle tension; Koo et al. 2013; Maïsetti et al. 2012), and GAS fascicle length was determined using ultrasonography assessment in B-mode. Thus, no changes were observed for both variables after the submaximal static stretching protocols, except for the R80 condition where the shear elastic modulus decreased. This suggests that effects on muscle may occur only for intensities above 80 % of maximal ROM. In respect to the stretching effects on tendon, it should be noted that we did not measure tendon properties. Indeed, the tendon length change based on the fascicle length change considering that these two elements are disposed in series (Kay and Blazevich 2009; Morse et al. 2008), and therefore a change in fascicle length would imply a change in tendon length. However, more direct measurements of tendon properties should be performed in a future study to confirm our results. In summary, several conclusions were obtained in this study. It was observed in this study that the relative medial gastrocnemius relaxation is independent of muscle–tendon unit length; and the fascicle length does not change during static stretching. In addition, the decrease of ankle passive torque after static stretching does not mean change in the medial gastrocnemius passive tension or fascicle length. The stretching effects on joint and muscle depends on its intensity, since stretching at 40 and 60 % of maximal dorsiflexion range of motion did not affect medial gastrocnemius shear elastic modulus. Also, the results of the present study suggest that stretching effects and relaxation may not be homogeneous among structures that cross the joint. Therefore, future studies should assess the relative contributions of the muscular and non-muscular structures crossing the joint. For that purpose, the use of elastography to study stretching presents very relevant perspectives.

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Conflict of interest The authors declare no conflict of interest.

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