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Influence of low muscle activation levels on the ankle torque and muscle shear modulus during plantar flexor stretching

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ABSTRACT

During stretching studies, surface electromyography (sEMG) is used to ensure the passive state of the muscle, for the characterization of passive muscle mechanical properties. Different thresholds (1%, 2% or 5% of maximal) are indifferently used to set “passive state”. This study aimed to investigate the effects of a slight activity on the joint and muscle mechanical properties during stretching.

The joint torque and muscle shear modulus of the *triceps surae* muscles were measured in fifteen healthy volunteers during ankle dorsiflexions: i) in a “fully relaxed” state, ii) during active conditions where participants were asked to produce an sEMG amplitude of 1%, 2% or 5% of their maximal sEMG amplitude of the *triceps surae*. The 1% condition was the only that did not result in significant differences in joint torque or shear modulus compared to the relaxed condition. In the 2% condition, increases in joint torque were found at 80% of the maximal angle in dorsiflexion, and in the shear modulus of *gastrocnemius medialis* and *gastrocnemius lateralis* at the maximal angle in dorsiflexion. During the 5% condition, joint torque and the shear modulus of *gastrocnemius medialis* were higher than during relaxed condition at angles larger than 40% of maximal angle in dorsiflexion. The results provide new insights on the thresholds that should be considered for the design of stretching studies. A threshold of 1% seems much more appropriate than a 2% or 5% threshold in healthy participants. Further studies are required to define similar thresholds for patients.

INTRODUCTION

Passive mechanical properties are important components of muscle function (Proske & Morgan, 1999; Azizi, 2014) and are related to muscle extensibility (Gajdosik, 2001). Several studies have shown the importance of measuring these properties to understand acute or chronic adaptations after trauma (Shelbourne *et al.*, 1996), injury (Diong *et al.*, 2012), immobilization (de Boer *et al.*, 2007), or training (Fouré *et al.*, 2013). In humans, the majority of studies evaluating these properties measure the passive joint [for review, see Magnusson (1998); Gajdosik (2001)], muscle fascicle length [using B-mode ultrasound, (Herbert *et al.*, 2002)] or muscle shear modulus using shear wave elastography (Maïsetti *et al.*, 2012). To accurately reflect passive mechanical properties, these approaches require the muscle to be fully inactive during stretch.

To ensure that muscles are in a passive state, it is important to monitor muscle activation to detect any unwanted activity that might influence the passive joint torque, the muscle fascicle length or the muscle shear modulus. For that purpose, myoelectrical activity is often measured through surface electromyography (sEMG) (McNair & Portero, 2005). The amplitude of the sEMG signal is then normalized to measurements during isometric maximal voluntary contractions (MVC) (McNair & Portero, 2005). Most of previous studies considered muscle to be passive when the sEMG amplitude remained below a given threshold (Gajdosik, 2001). However, a wide range of thresholds has been used to qualify such a passive state: 1% (McNair *et al.*, 2001), 2% (Nordez *et al.*, 2010), 5% (Gajdosik *et al.*, 2005), up to 10% of the maximal activation (Halbertsma *et al.*, 1999; Bar-On *et al.*, 2018). As some of these thresholds were relatively high, it is likely that low activation was present during a supposedly passive stretch. To our knowledge, only Foo *et al.* (2019) reported that hamstring activity might decrease the range of motion of the hip joint during a straight leg raise test (-0.6° for every increase of 1% in myoelectrical activation). The effects of such low muscle activation on muscle mechanical properties are still misunderstood. Even though activation as low as 1% of maximal activation are likely to have minimal influence, it is necessary to determine activation levels that significantly affect the estimation of muscle mechanical properties.

The present study was designed to quantify the effect of low muscle activation levels on the mechanical

properties of ankle joint and *triceps surae* (TS) muscles. Ankle joint was chosen here because ankle joint torque and TS mechanical properties are often examined in stretching studies. To this end, joint torque and shear modulus of the three heads of TS were measured while the ankle was dorsiflexed by an ergometer. Participants were asked to produce low muscle activation using a visual feedback of sEMG amplitude (detailed below in protocol; at 1%, 2% and 5 % of maximal sEMG amplitude) or to stay fully passive [named “relaxed” condition] where participants were asked to stay as relaxed as possible during stretching.

METHODS

Participants

A sample size calculation for the study was based on analyse of variance (ANOVA repeated measures, within-between interactions) for testing the association at 5% level between the conditions, angles, and muscle shear modulus. Using an effect size of $\eta_p^2=0.14$ and a power of 0.95, 12 participants would be required to detect significant difference [Gpower 3.1.9.2; Faul *et al.* (2007)]. Fifteen healthy participants (male/female: 12/3; age: 24.1±4.3 years; height: 177±7 cm; body mass: 65.5±14.9 kg) volunteered to participate in this study. The study received Institutional Ethics Committee approval (CPP-MIP-015). The procedures conformed to the Declaration of Helsinki.

Equipment

Ergometer

An isokinetic dynamometer (Biodex 3 Medical, Shirley, New York, USA) was used. The ankle joint was carefully aligned with the center of rotation of the ergometer by and experienced user (Bruening *et al.*, 2008). 0° of ankle dorsiflexion was defined as the foot sole is perpendicular to the tibia, and negative angles relative to plantarflexion (PF). Additional thermoformable customed-device and adhesive non-elastic taping to ergometer Velcro-straps were realized to avoid foot or heel motion. Ankle angles and joint torque were recorded using an external 16-bit analog/digital converter (1 kHz, 16-35 PowerLab ADInstruments Inc., Colorado Springs, USA).

Surface electromyography (sEMG)

The myoelectrical activity of the *gastrocnemius medialis* and *gastrocnemius lateralis* (GM and GL, respectively), the *soleus* (SOL) and the *tibialis anterior* (TA) were recorded using hydrogel adhesive surface electrodes (KendallTM 100 foam-series, Covidien, Mansfield, USA). The skin was prepared according to the SENIAM guidelines (Hermens *et al.*, 2000). Due to overlapping probe locations on the skin, ultrasound imaging ensured that the electrodes were positioned appropriately: longitudinally with respect to the muscle fascicle alignment, and away from neighboring muscles (Lacourpaille *et al.*, 2017). sEMG signals were amplified with a biosignal amplifier (g.BSamp 0201a, Guger Technologies, Schiedlberg, Austria; gain =1000) and digitized together with mechanical signals using the same acquisition system (see Ergometer) at a sampling rate of 1 kHz. For each muscle, the sEMG signal was filtered (band-pass: 20-400 Hz and band-stop: 50 Hz) in order to remove unwanted noise associated with artifacts. The signals were quantified in terms of root mean square (EMG-RMS) using a moving average window (300 ms width, LabChart v7.0, Inc., Colorado Springs, USA). The EMG-RMS signals for each muscle (GM, GL, SOL, and TA) was normalized to the maximal EMG-RMS value recorded during MVC. The EMG-RMS of TS was provided in real time on a computer screen (Figure 1). The quality of the sEMG signals was evaluated by calculating i) the baseline noise in % of the maximal value reached during MVC; ii) a signal-to-noise ratio (SNR, Matlab® function *snr*) (Table 1).

Shear wave elastography (SWE)

An ultrasound scanner (Supersonic Imagine, v. 6.1, Aix-en-Provence, France) coupled with a linear transducer [2–10 MHz for SOL or 4–15 MHz for GM and GL, Supersonic Imagine, Aix-en-Provence, France] was used in shear wave elastography mode (MSK preset, penetration mode, spatial smoothing 5/9, persistence off, scale: 0-600 kPa). The shear modulus (μ) is related to the shear wave velocity (V_s) measured using elastography:

$$\mu = \rho V_s^2 \text{ (Equation 1)}$$

where ρ the density of the tissue (1000 kg.m⁻³ for muscle).

The shear modulus has been shown to have strong linear relationship with Young's modulus (R^2 between 0.916-0.988) (Eby *et al.*, 2013; Koo *et al.*, 2013) and thus, can be used as an index of changes in muscle

stiffness (Hug *et al.*, 2015). The transducer was aligned along the longitudinal axis of the leg (i.e., the direction of shortening/lengthening) and perpendicular to the skin so that the image plane perpendicularly intersects the muscle aponeurosis (Le Sant *et al.*, 2017). Previous results from our team showed very good reliability of SWE for measuring the shear modulus of *triceps surae* muscles during stretching (Le Sant *et al.*, 2017). A transistor-transistor logic pulse (duration <50 ms) was sent by the ultrasound scanner at each shear modulus measurement (i.e. each second) that allowed to synchronize shear modulus measurements with the ankle angle, passive torque and sEMG signals.

Protocol

Participants first performed a familiarization session. They laid prone on the ergometer with the ankle to be tested firmly strapped to the footplate of the device. First, the participants performed 3 isometric MVCs (separated by a rest of 90 s) in PF and in DF, respectively. Second, the maximal angle in DF (max DF) was defined. For that purpose, the ankle was moved by the ergometer at 2°/s, and participants pressed a button when they felt their maximum tolerable stretch limit (onset of pain in the posterior region of the leg). The highest angle obtained during three trials was kept as their maximal DF. Three conditioning cycles (from 40° of PF to max DF, 2°/s) were then performed (Nordez *et al.*, 2008). Third, participants underwent stretching at 2°/s for each condition [1%, 2%, 5% of maximal EMG-RMS(TS) and “relaxed” conditions]. The peak EMG-RMS(TS) from maximal plantarflexion was used to calculate submaximal levels. Participants were asked to maintain a given muscle activity level during the ankle motion, using feedback provided in real time on a screen (Figure 1). The familiarization continued until satisfactory, i.e. if the averaged muscle activity [EMG-RMS(TS)] corresponded to the targeted level \pm ~0.5%. All the participants were able to perform the task and completed the second session dedicated to data collection.

The second session was performed between one and seven days after the familiarization session. The procedures were repeated: MVCs, maximal ROM assessments, and conditioning. Then, the participants were asked to match a target during ankle dorsiflexions (40° of PF to max DF, 2°/s) at either 1%, 2%, 5% of maximal EMG-RMS(TS) or during the “relaxed” condition (random order). For each condition, three dorsiflexions were performed such that the shear modulus of each muscle of the TS was measured

(random order). The transducer was placed over the mid muscle region for GM and GL, and over the distal region for SOL, as defined in Le Sant *et al.* (2017). A total of twelve dorsiflexions were realized (4 conditions x 3 muscles) during which the joint torque, shear modulus of one muscle and muscle activity levels of four muscles were measured.

Data analysis

Data were processed using Matlab® scripts (The MathWorks Inc., Natick, USA) as previously described in details (Le Sant *et al.*, 2017). Shear modulus values were averaged over the largest region of interest (ROI) that avoided aponeurosis and artefacts (average surface of 92 mm², 89 mm² and 86 mm² for the GM, GL and SOL). Angle and joint torque were filtered (Butterworth low-pass filter, cutoff 10Hz) and torque corrected for gravity. Maximal EMG-RMS for each muscle corresponded to the peak value reached during MVC. For each trial, the EMG-RMS of each muscle (moving windows width: 300 ms) and joint torque were calculated for each shear modulus measurement (ie. at 1 Hz, timing determined by using the transistor-transistor logic pulse sent by the ultrasound scanner). Because the max DF angle differed among individuals, the angle was normalized to the maximal ROM (i.e., 0% as 40° PF, and 100% as the max DF). Then, EMG-RMS, passive torque and shear modulus values were calculated every 5% (i.e., 21 values) using linear interpolation.

Statistics

The data were processed using Statistica® (v.10, Statsoft Inc., Tulsa, USA). Data passed the Shapiro-Wilk normality test. For each condition, the averaged value of the 3 trials was used for joint torque and RMS-EMG. The changes in the measured EMG-RMS across conditions were assessed using a repeated-measures ANOVA (4 conditions x 4 angles x 3 muscles). The four conditions were “relaxed”, 1%, 2%, and 5% of max EMG-RMS(TS). The four angles corresponded to the angle reached by each participant at 0%, 40%, 80% and 100% (i.e., max DF) of ankle ROM. Another repeated measures ANOVA (4 conditions x 4 angles) was used to assess changes in EMG-RMS(TA). These analyses were realized to confirm that the conditions were well achieved (ie, targeted level, without any potential influences of TA). In addition, we wanted to assess whether conditions affect in the same way or not the various muscles depending on joint angles. Two repeated-measures ANOVAs were conducted to assess the

impact of the condition on joint torque (4 conditions x 4 angles) and on shear modulus (4 conditions x 4 angles x 3 muscles [GM, GL and SOL]). We hypothesized an increase in joint torque and muscle shear modulus at a same ankle angle with the increasing level of muscle activity. Partial eta square (η_p^2) was reported as effect-size estimation. Small, medium and large effects were considered for $\eta_p^2 = 0.01$, $\eta_p^2 = 0.07$ and $\eta_p^2 \geq 0.14$, respectively (Cohen, 1988). To account for hidden multiplicity in exploratory multiway ANOVA, a Benjamini-Hochberg procedure was used as described in Cramer *et al.* (2016). The p-values from the ANOVAS were sorted in ranks from smallest to largest (7 ranks for RMS-EMG, 3 ranks for torque, 7 ranks for shear modulus, respectively) and were judged significant if inferior to the corresponding Benjamini-Hochberg critical value (Benjamini & Hochberg, 1995). Post-hoc analyses were performed using Bonferroni correction. In order to better describe the small differences between the “relaxed” and 1% conditions, Bland-Altman plots were generated to study the agreements for joint torque, shear modulus and muscle activity (Bland & Altman, 1986). The statistical significance was set at $p < 0.05$. Data are reported as mean \pm standard deviation (SD).

RESULTS

The averaged \pm SD angles were $-40.0 \pm 0.4^\circ$ PF (0%), $-10.0 \pm 2.6^\circ$ PF (40%), $20.2 \pm 5.3^\circ$ DF (80%) and $35.3 \pm 6.6^\circ$ DF (100%), respectively (Figures 1 to 4).

Effects of condition on muscle activation

The averaged EMG-RMS of the TS were $0.4 \pm 0.1\%$ (range 0.2%-0.7%), $1.2 \pm 0.2\%$ (range 0.9%-1.6%), $2.1 \pm 0.3\%$ (range 1.7%-2.7%) and $4.8 \pm 0.7\%$ (range 4.3%-6.7%) of max EMG-RMS(TS) for the “relaxed”, 1%, 2% and 5% conditions, respectively (Figure 2).

As expected, there was a main effect of condition ($F(3,42)=417.96$, $p < 0.001$, $\eta_p^2 = 0.97$) indicating an increase in EMG-RMS among TS muscles with the increase in activation level target. Main effects of angle ($F(3,42)=6.62$, $p < 0.001$, $\eta_p^2 = 0.32$), and muscle ($F(2,28)=6.13$, $p = 0.006$, $\eta_p^2 = 0.30$) were also found. Condition x muscle ($F(6,84)=5.12$, $p < 0.001$, $\eta_p^2 = 0.27$), condition x angle ($F(9,126)=3.39$, $p < 0.001$, $\eta_p^2 = 0.19$), muscle x angle ($F(6,84)=23.65$, $p < 0.001$, $\eta_p^2 = 0.63$), and condition x muscle x angle ($F(18,252)=21.12$, $p < 0.001$, $\eta_p^2 = 0.59$) interactions were also significant. Post-hoc analyses

revealed an increase in EMG-RMS(SOL) at 80% and at max DF during the 2% and 5% conditions (all p-values <0.001) and a decrease in EMG-RMS(GM) at max DF (p<0.001) and in EMG-RMS(GL) during the 5% condition (all p-values <0.005). Regarding the TA, there were main effects of condition ($F(3,42)=32.62$, $p<0.001$, $\eta_p^2 = 0.70$) and angle ($F(3,42)=4.09$, $p=0.012$, $\eta_p^2 = 0.23$), but the interaction condition x angle was not significant ($F(9,126)=0.78$, $p=0.64$). EMG-RMS(TA) was significantly higher during 5% condition than during the other conditions (all p-values<0.018). During the 2% condition, EMG-RMS(TA) was higher at max DF than at 40% and 80% (p<0.001 and p=0.032, respectively). During the 5% condition, EMG-RMS(TA) was higher at max DF (all p-values<0.008) (Figure 2). In addition, regardless the muscle, EMG-RMS was not different between the “relaxed” and the 1% conditions (all p-values>0.11). The mean difference between “relaxed” and 1% EMG-RMS was 0.77±0.11% for the GM, 0.51±0.05% for the GL, 0.97±0.13% for the SOL, and 0.10±0.32% for the TA (Supplementary File 1).

Effects of muscle activation on joint torque

A significant main effect of condition ($F(3,42)=56.56$, $p<0.001$, $\eta_p^2 = 0.80$) and angle ($F(3,42)=268.97$, $p<0.001$, $\eta_p^2 = 0.94$) were found. There was also a significant interaction condition x angle ($F(9,126)=26.23$, $p<0.001$, $\eta_p^2 = 0.65$). Compared to the “relaxed” condition, joint torque was not different for the 1% condition (all p-values>0.41). The mean difference between “relaxed” and 1% torque values was 1.2±1.9N.m (Supplementary File 1). When compared to the relaxed condition, joint torque was significantly larger in the 5% condition at 40%, 80% and max DF angles, and in the 2% condition at 80% and max DF angles (all p-values<0.001) (Figure 3). At max DF, joint torque was 44.5±12.0N.m, 46.5±11.8N.m, 50.3±12.4N.m, and 57.7±12.6N.m, for the “relaxed”, 1%, 2%, and 5% conditions, respectively (Figure 3). When compared to the “relaxed” condition, the peak torque was increased by 33±24% for the 5% condition, and by 14±10% for the 2% condition.

Effects of muscle activation on shear modulus

The main effects of condition ($F(3,42)=55.01$, $p<0.001$, $\eta_p^2 = 0.80$), muscle ($F(2,28)=67.05$, $p<0.001$,

$\eta_p^2 = 0.83$) and angle ($F(3,42)=256.90$, $p<0.001$, $\eta_p^2 = 0.95$) were found on shear modulus (Figure 4). There were also significant interactions: condition x muscle ($F(6,84)=4.96$, $p<0.001$, $\eta_p^2 = 0.26$), condition x angle ($F(9,126)=13.30$, $p<0.001$, $\eta_p^2 = 0.58$), muscle x angle ($F(6,84)=65.64$, $p<0.001$, $\eta_p^2 = 0.82$) and condition x muscle x angle ($F(18,252)=2.62$, $p<0.001$, $\eta_p^2 = 0.16$). When the 2% condition was compared to the relaxed condition, the only significant differences in shear modulus were found for GM and GL at max DF ($p<0.001$) (Figure 4). When the 5% condition was compared to the relaxed condition, significant differences were found at 40%, 80% and max DF for GM (all p -values <0.001), and at 80% and max DF for GL and SOL (all p -values <0.002), respectively. When compared to the “relaxed” condition, the peak shear modulus was increased by $26\pm 20\%$, $19\pm 9\%$ and $49\pm 41\%$ for the 2% condition, and by $55\pm 40\%$, $38\pm 13\%$ and $100\pm 87\%$ for the 5% condition, for GM, GL and SOL, respectively. No significant differences were found for the shear modulus between “relaxed” and 1% conditions (all p -values=1.000). The mean difference between the “relaxed” and 1% shear modulus was 2.9 ± 0.9 kPa for the GM, 1.7 ± 0.6 kPa for the GL, and 1.4 ± 0.7 kPa for the SOL (Supplementary File 1).

DISCUSSION

This study describes the effects of muscle activation levels that are usually considered ‘negligible’ during passive stretching on both joint torque and muscle shear modulus. The main finding was that muscle activation higher than 1% affects the joint torque and shear modulus, which increase with ankle dorsiflexion. In the 5% condition, the effect was evident at low angles (i.e., 40% of maximal DF) (Figures 3 and 4).

Measuring myoelectrical activity during stretching studies is used to confirm the absence of unwanted muscle activation (McNair & Portero, 2005). This is crucial because muscle activation, albeit small, may affect muscle mechanical properties. For that purpose, participants are trained to stay “as relaxed as possible” and their spontaneous myoelectrical activity is measured during joint rotation (McNair & Portero, 2005). According to these studies, intrinsic stiffness and muscle activation should both contribute to joint torque in the last degrees of ankle’s ROM towards DF. As a result of the study conducted by McNair *et al.* (2001), 80% of the max DF is commonly used to limit this unwanted activity. Beyond this ankle angle, myoelectrical activity was shown to increase significantly (McNair *et al.*,

2001). In our study, a significant increase in the EMG-RMS of TS at 80% of max DF was only found during the 2% and 5% conditions. The results also revealed that it is possible for participants to maintain a very low level of myoelectrical activity among TS during stretching [$0.4 \pm 0.1\%$ of max EMG-RMS(TS), during the “relaxed condition” Figure 2]. We think that the familiarization session was helpful to obtain low EMG values during the stretching in the relaxed condition.

Regarding the shear modulus, the values reached at max DF were the highest for GM when compared to GL and SOL, whatever the tested condition. This result is in accordance with previous studies that reported between-muscle differences in shear modulus among plantar flexors under ‘relaxed’ conditions (Hirata *et al.*, 2015; Hirata *et al.*, 2016; Le Sant *et al.*, 2017; Le Sant *et al.*, 2018). Considering that the GM cross-sectional area is larger than that of GL (Fukunaga *et al.*, 1992), passive force developed by the GM muscle during stretch is likely much larger than that produced by the GL muscle. However, considering a lower shear modulus for the SOL compared to the GM and GL and a higher volume, it is more difficult to estimate the contribution to the passive torque of the SOL using the methods of this study.

A threshold such as 5% of EMG-RMS(TS) is often used to evaluate elderly patients (Gajdosik *et al.*, 2004, 2005) or people with neurological conditions (Kalkman *et al.*, 2018; Le Sant *et al.*, 2018). Such an activity level could have significantly influenced the results of these studies (Figures 3 and 4). Our results indicate that using such a threshold could induce an overestimation of 64% and 33% for the muscle shear modulus and passive torque, respectively. However, because of structural differences with young populations (e.g., muscle volume, intra-muscular connective/adipose composition) it is difficult to estimate how much a 5% of EMG-RMS(TS) might have influenced the shear modulus and joint torque among elderly/patient populations. In addition, it remains difficult to be sure that patients reached maximal activity levels during MVC. It should have influenced the activity levels measured during stretching in previous studies with patients (Kalkman *et al.*, 2018; Le Sant *et al.*, 2018). Thus, further studies should be conducted in patients to assess the effects of unwanted EMG activity on passive torque and muscle behaviour during stretching. The use of motor blocks could help isolate the passive contribution to joint stiffness (Deltombe *et al.*, 2004; Bollens *et al.*, 2011). Few studies have assessed the impact of this approach on biomechanical parameters (Bleyenheuft *et al.*, 2008; Buffenoir *et al.*,

2013). The aforementioned studies showed that the passive resistance of the ankle joint was decreased after a selective block conducted at the superior *soleus* nerve. However, since they used sinusoidal perturbations applied to the ankle joint at different frequencies, it remains difficult to interpret those results in the context of classical stretching studies. Future studies, assessing the impact of nerve blocs of the TS could help to understand the impact of muscle activation ‘at rest’ (such as spastic dystonia) on the mechanical properties of the TS during stretching.

This study was designed to measure the effects of minimal activity on ankle joint and TS muscle mechanical properties during stretching. As described, a feedback EMG-RMS(TS) was used, based on an average EMG-RMS for the three heads of the TS, and an amplitude-normalization procedure (i.e., maximal EMG-RMS during MVC). This procedure supposes a high sensibility of sEMG to detect very low levels of muscle activity. Other techniques such as high-density EMG or intramuscular EMG using fine wires might have been more direct approaches of measurement. We chose our experimental set-up because it is used in classical stretching studies. The high maximal/baseline ratios, SNR values and Bland-Altman results make us confident that our procedures were appropriate, in particular for the lowest conditions (“relaxed” *versus* 1%). Participants reached and maintained the targeted levels during submaximal conditions (1%, 2% and 5%) using a biofeedback of normalized EMG-RMS(TS) provided in real time (Figure 1). While the mean values were in accordance with the targets of the feedback, some

inter-individual variability was present (average of $\pm 0.32\%$ in regard of the targeted level) but, the ranges of sEMG activity levels reached clearly showed that there was no overlap between conditions.

However, the contributions of GM, GL and SOL to the EMG-RMS(TS) were not constant, in particular during the 5% condition (Figure 2). It seems that a specific coordination between muscles occurred with a decrease in the activity of the *gastrocnemii* combined with an increase in the activity of SOL. These changes in muscle activity for such low levels were not expected to occur. Their mechanical consequences on joint torque are difficult to evaluate, but did not lead to visible changes in the shear modulus-angle relationships. However, this point would not alter the main conclusions of the present paper and the observations for the most active conditions (e.g., 5% of maximal) compared to the “relaxed” condition. As previously described in the method, the joint axis of rotation was carefully

aligned with the axis of rotation of the ergometer. To our knowledge, the influence of a possible

misalignment on the joint torque measured during passive stretching has not been quantified in the literature. However, considering that the foot was very firmly strapped in the present study, and movement of the foot are generally lower in passive conditions compared to maximal isometric contractions, we think that the effect of foot motion was small. It was confirmed in a previous study (Ates *et al.*, 2018) that found a mean difference in ankle angle of 1.4° (Confidence Interval 95% 1.3°;1.6°) between the ergometer and 3 optoelectronic system during a pilot-testing (n=6, range of -20°PF to 20°DF). Therefore, this effect was probably small and marginally influenced our results. Due to potential various joint configuration (e.g., muscle volume, lever arm...) and neuromechanical properties (eg EMG-force relationships), it is difficult to extrapolate the results of the present study to other the joints and muscles. Therefore, further studies are needed to examine the effects of muscle activity during stretching on other joints (e.g., knee torque) with different structure/architecture.

CONCLUSION

This study showed that joint stiffness and muscle shear modulus (in particular GM) were higher if participants activated their TS muscle at 5% of its maximal voluntary , activation (measured by sEMG), during slow dorsiflexions of the ankle. A lower level of EMG amplitude (2%) had significant influence on joint torque and shear modulus at the end of the range of dorsiflexion. These results provide new insights that might be useful for the design of future stretching studies, as 5% has classically been used as a threshold to describe a “passive state”. A threshold of 1% seems more appropriate for healthy participants. Further studies are required to set acceptable EMG thresholds for patients.

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350 **REFERENCES**

- 351 **Ates, F., Andrade, R. J., Freitas, S. R., Hug, F., Lacourpaille, L., Gross, R., . . . Nordez, A.**
 352 (2018). Passive stiffness of monoarticular lower leg muscles is influenced by knee joint angle.
 353 *European Journal of Applied Physiology*, 118(3), 585-593. doi: 10.1007/s00421-018-3798-y
- 354 **Azizi, E.** (2014). Locomotor function shapes the passive mechanical properties and operating
 355 lengths of muscle. *Proceedings: Biological Sciences*, 281(1783), 20132914. doi:
 356 10.1098/rspb.2013.2914
- 357 **Bar-On, L., Kalkman, B. M., Cenni, F., Schless, S.-H., Molenaers, G., Maganaris, C. N., .**
 358 **. . Desloovere, K.** (2018). The Relationship Between Medial Gastrocnemius Lengthening
 359 Properties and Stretch Reflexes in Cerebral Palsy. *Frontiers in Pediatrics*, 6(259). doi:
 360 10.3389/fped.2018.00259
- 361 **Benjamini, Y., & Hochberg, Y.** (1995). Controlling the False Discovery Rate: A Practical and
 362 Powerful Approach to Multiple Testing *Journal of the Royal Statistical Society. Series B*
 363 *(Methodological)*, 57(1), 289-300.
- 364 **Bland, J. M., & Altman, D. G.** (1986). Statistical methods for assessing agreement between
 365 two methods of clinical measurement. *Lancet*, 1(8476), 307-310.
- 366 **Bleyenheuft, C., Detrembleur, C., Deltombe, T., Fomekong, E., & Lejeune, T. M.** (2008).
 367 Quantitative assessment of anaesthetic nerve block and neurotomy in spastic equinus foot: a
 368 review of two cases. *Journal of rehabilitation medicine*, 40(10), 879-881. doi:
 369 10.2340/16501977-0263
- 370 **Bollens, B., Deltombe, T., Detrembleur, C., Gustin, T., Stoquart, G., & Lejeune, T. M.**
 371 (2011). Effects of selective tibial nerve neurotomy as a treatment for adults presenting with
 372 spastic equinovarus foot: a systematic review. *Journal of rehabilitation medicine*, 43(4), 277-
 373 282. doi: 10.2340/16501977-0786
- 374 **Bruening, D. A., Crewe, A. N., & Buczek, F. L.** (2008). A simple, anatomically based
 375 correction to the conventional ankle joint center. *Clinical biomechanics (Bristol, Avon)*, 23(10),
 376 1299-1302. doi: 10.1016/j.clinbiomech.2008.08.005
- 377 **Buffenoir, K., Decq, P., Lambertz, D., & Perot, C.** (2013). Neuromechanical assessment of
 378 lidocaine test block in spastic lower limbs. *Applied Physiology, Nutrition, and Metabolism*,
 379 38(11), 1120-1127. doi: 10.1139/apnm-2013-0070
- 380 **Cohen, J.** (1988). In L. E. Associates (Ed.), *Statistical Power Analysis for the Behavioral*
 381 *Sciences* (pp. 273-406). Hillsdale (NJ).
- 382 **Cramer, A. O., van Ravenzwaaij, D., Matzke, D., Steingroever, H., Wetzels, R., Grasman,**
 383 **R. P., . . . Wagenmakers, E. J.** (2016). Hidden multiplicity in exploratory multiway ANOVA:
 384 Prevalence and remedies. *Psychon Bull Rev*, 23(2), 640-647. doi: 10.3758/s13423-015-0913-5
- 385 **de Boer, M. D., Maganaris, C. N., Seynnes, O. R., Rennie, M. J., & Narici, M. V.** (2007).
 386 Time course of muscular, neural and tendinous adaptations to 23 day unilateral lower-limb
 387 suspension in young men. *The Journal of physiology*, 583(Pt 3), 1079-1091. doi:
 388 10.1113/jphysiol.2007.135392
- 389 **Deltombe, T., De Wispelaere, J. F., Gustin, T., Jamart, J., & Hanson, P.** (2004). Selective
 390 blocks of the motor nerve branches to the soleus and tibialis posterior muscles in the
 391 management of the spastic equinovarus foot. *Archives of physical medicine and rehabilitation*,
 392 85(1), 54-58.
- 393 **Diong, J., Harvey, L. A., Kwah, L. K., Eyles, J., Ling, M. J., Ben, M., & Herbert, R. D.**
 394 (2012). Incidence and predictors of contracture after spinal cord injury--a prospective cohort
 395 study. *Spinal Cord*, 50(8), 579-584. doi: 10.1038/sc.2012.25

Eby, S. F., Song, P., Chen, S., Chen, Q., Greenleaf, J. F., & An, K. N. (2013). Validation of shear wave elastography in skeletal muscle. *Journal of biomechanics*, 46(14), 2381-2387. doi: 10.1016/j.jbiomech.2013.07.033

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39(2), 175-191.

Foo, Y., Heroux, M. E., Chia, L., & Diong, J. (2019). Involuntary hamstring muscle activity reduces passive hip range of motion during the straight leg raise test: a stimulation study in healthy people. *BMC Musculoskeletal Disorders*, 20(1), 130. doi: 10.1186/s12891-019-2511-6

Fouré, A., Nordez, A., & Cornu, C. (2013). Effects of eccentric training on mechanical properties of the plantar flexor muscle-tendon complex. *Journal of applied physiology* (Bethesda, Md. : 1985), 114(5), 523-537. doi: 10.1152/japplphysiol.01313.2011

Fukunaga, T., Roy, R. R., Shellock, F. G., Hodgson, J. A., Day, M. K., Lee, P. L., . . . Edgerton, V. R. (1992). Physiological cross-sectional area of human leg muscles based on magnetic resonance imaging. *Journal of Orthopaedic Research*, 10(6), 928-934. doi: 10.1002/jor.1100100623

Gajdosik, R. L. (2001). Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clinical biomechanics (Bristol, Avon)*, 16(2), 87-101.

Gajdosik, R. L., Vander Linden, D. W., McNair, P. J., Riggins, T. J., Albertson, J. S., Mattick, D. J., & Wegley, J. C. (2004). Slow passive stretch and release characteristics of the calf muscles of older women with limited dorsiflexion range of motion. *Clinical biomechanics (Bristol, Avon)*, 19(4), 398-406. doi: 10.1016/j.clinbiomech.2003.12.009

Gajdosik, R. L., Vander Linden, D. W., McNair, P. J., Riggins, T. J., Albertson, J. S., Mattick, D. J., & Wegley, J. C. (2005). Viscoelastic properties of short calf muscle-tendon units of older women: effects of slow and fast passive dorsiflexion stretches in vivo. *European Journal of Applied Physiology*, 95(2-3), 131-139. doi: 10.1007/s00421-005-1394-4

Halbertsma, J. P., Mulder, I., Goeken, L. N., & Eisma, W. H. (1999). Repeated passive stretching: acute effect on the passive muscle moment and extensibility of short hamstrings. *Archives of physical medicine and rehabilitation*, 80(4), 407-414.

Herbert, R. D., Moseley, A. M., Butler, J. E., & Gandevia, S. C. (2002). Change in length of relaxed muscle fascicles and tendons with knee and ankle movement in humans. *The Journal of physiology*, 539(Pt 2), 637-645. doi: D - NLM: PMC2290150 EDAT- 2002/03/08 10:00 MHDA- 2002/06/05 10:01 CRDT- 2002/03/08 10:00 AID - PHY_12756 [pii] PST - ppublish

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*, 10(5), 361-374.

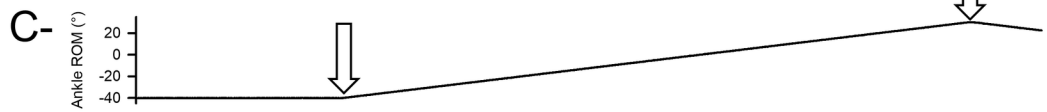
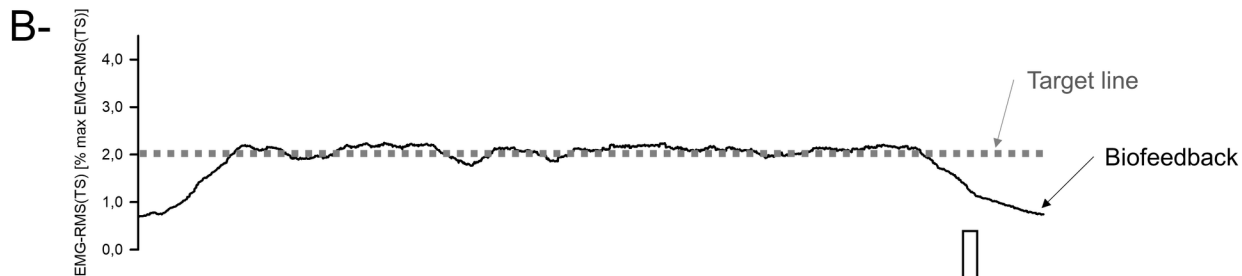
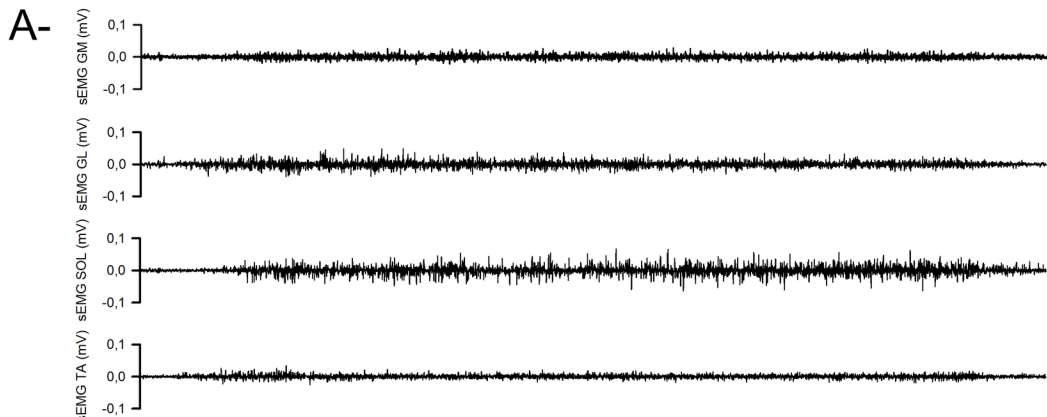
Hirata, K., Kanehisa, H., Miyamoto-Mikami, E., & Miyamoto, N. (2015). Evidence for intermuscle difference in slack angle in human triceps surae. *Journal of biomechanics*, 48(6), 1210-1213. doi: 10.1016/j.jbiomech.2015.01.039

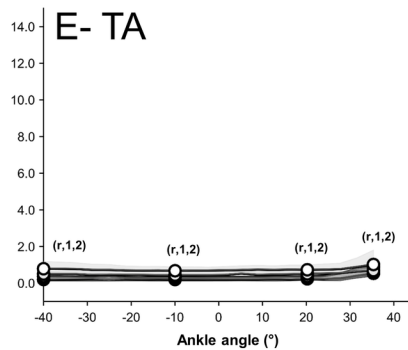
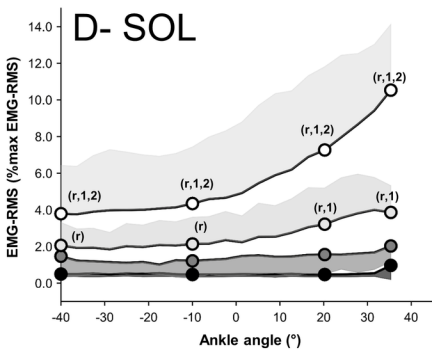
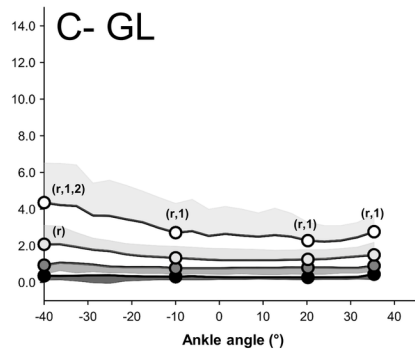
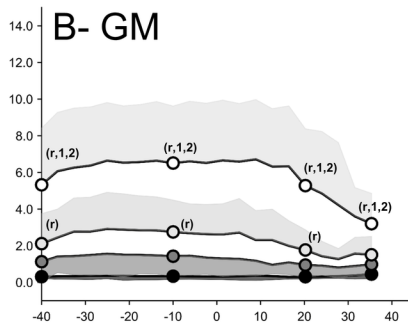
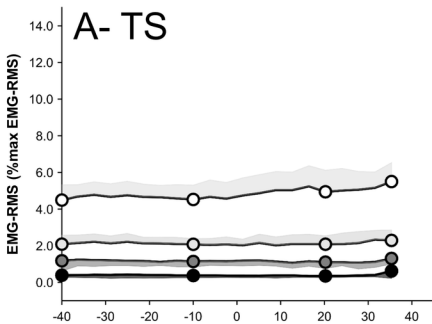
Hirata, K., Miyamoto-Mikami, E., Kanehisa, H., & Miyamoto, N. (2016). Muscle-specific acute changes in passive stiffness of human triceps surae after stretching. *European Journal of Applied Physiology*, 116(5), 911-918. doi: 10.1007/s00421-016-3349-3

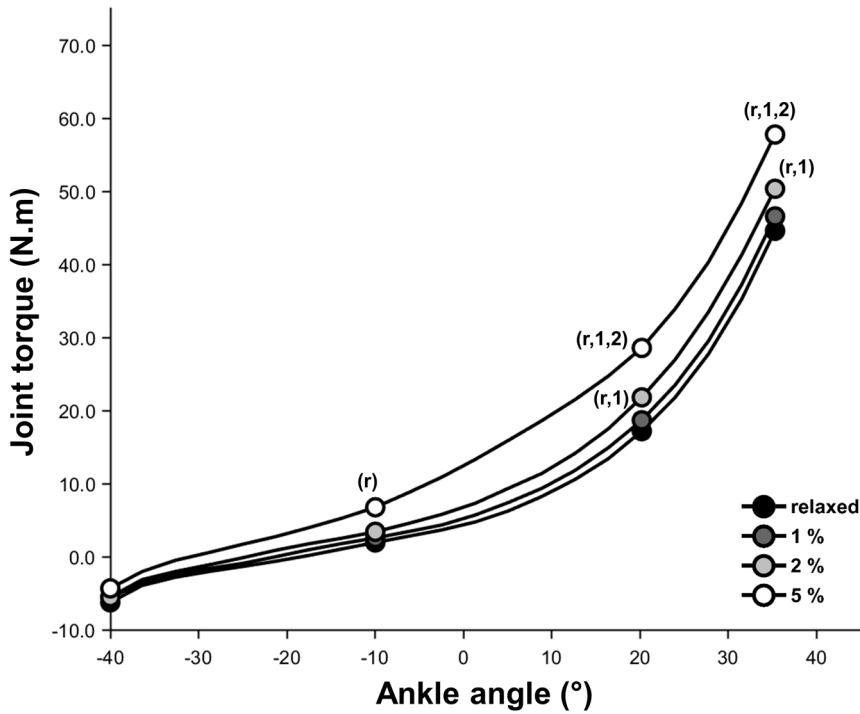
Hug, F., Tucker, K., Gennissou, J. L., Tanter, M., & Nordez, A. (2015). Elastography for Muscle Biomechanics: Toward the Estimation of Individual Muscle Force. *Exercise and Sport Sciences Reviews*, 43(3), 125-133. doi: 10.1249/JES.0000000000000049

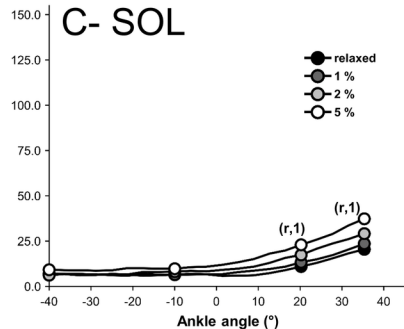
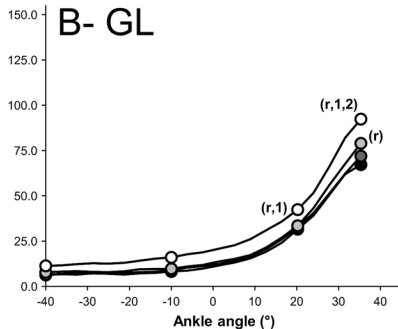
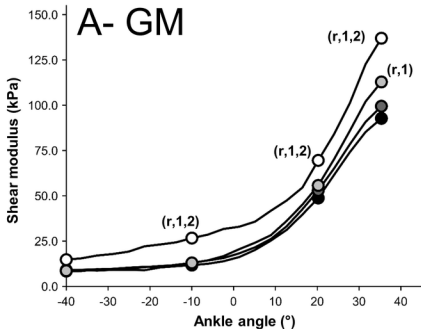
Kalkman, B. M., Bar-On, L., Cenni, F., Maganaris, C. N., Bass, A., Holmes, G., . . . O'Brien, T. D. (2018). Muscle and tendon lengthening behaviour of the medial gastrocnemius during ankle joint rotation in children with cerebral palsy. *Experimental Physiology*. doi: 10.1113/ep087053

- Koo, T. K., Guo, J. Y., Cohen, J. H., & Parker, K. J.** (2013). Relationship between shear elastic modulus and passive muscle force: an ex-vivo study. *Journal of biomechanics*, 46(12), 2053-2059. doi: 10.1016/j.jbiomech.2013.05.016
- Lacourpaille, L., Nordez, A., & Hug, F.** (2017). The nervous system does not compensate for an acute change in the balance of passive force between synergist muscles. *Journal of Experimental Biology*, 220(Pt 19), 3455-3463. doi: 10.1242/jeb.163303
- Le Sant, G., Nordez, A., Andrade, R., Hug, F., Freitas, S., & Gross, R.** (2017). Stiffness mapping of lower leg muscles during passive dorsiflexion. *Journal of anatomy*, 230(5), 639-650. doi: 10.1111/joa.12589
- Le Sant, G., Nordez, A., Hug, F., Andrade, R., Lecharte, T., McNair, P., & Gross, R.** (2018). Effects of stroke injury on the shear modulus of the lower leg muscle during passive dorsiflexion. *Journal of applied physiology (Bethesda, Md. : 1985)*. doi: 10.1152/japplphysiol.00968.2017
- Magnusson, S. P.** (1998). Passive properties of human skeletal muscle during stretch maneuvers. A review. *Scand J Med Sci Sports*, 8(2), 65-77.
- Maïsetti, O., Hug, F., Bouillard, K., & Nordez, A.** (2012). Characterization of passive elastic properties of the human medial gastrocnemius muscle belly using supersonic shear imaging. *Journal of biomechanics*, 45(6), 978-984. doi: 10.1016/j.jbiomech.2012.01.009
- McNair, P., & Portero, P.** (2005). Using isokinetic dynamometers for measurements associated with tissue extensibility. *Iso Exerc Sci*, 13(1), 53-56.
- McNair, P. J., Dombroski, E. W., Hewson, D. J., & Stanley, S. N.** (2001). Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. *Medicine and science in sports and exercise*, 33(3), 354-358. doi: 10.1097/00005768-200103000-00003
- Nordez, A., McNair, P., Casari, P., & Cornu, C.** (2008). Acute changes in hamstrings musculo-articular dissipative properties induced by cyclic and static stretching. *International journal of sports medicine*, 29(5), 414-418. doi: 10.1055/s-2007-964980
- Nordez, A., McNair, P. J., Casari, P., & Cornu, C.** (2010). Static and cyclic stretching: their different effects on the passive torque-angle curve. *Journal of science and medicine in sport / Sports Medicine Australia*, 13(1), 156-160. doi: 10.1016/j.jsams.2009.02.003
- Proske, U., & Morgan, D. L.** (1999). Do cross-bridges contribute to the tension during stretch of passive muscle? *Journal of muscle research and cell motility*, 20(5-6), 433-442.
- Shelbourne, K. D., Patel, D. V., & Martini, D. J.** (1996). Classification and management of arthrofibrosis of the knee after anterior cruciate ligament reconstruction. *The American journal of sports medicine*, 24(6), 857-862. doi: 10.1177/036354659602400625









Muscle	EMG-RMS(baseline)/EMG-RMS(MVC) (%)	Signal to Noise Ratio (dB)
GM	0.35±0.11	37.8±3.1
GL	0.32±0.15	37.6±4.3
SOL	0.44±0.18	33.1±3.7
TA	0.33±0.22	42.7±3.7

Table 1 – Quality of the myoelectrical activity recorded for each muscle during data collection.

Data are shown as mean±standard deviation.

Legend: GM: gastrocnemius medialis; GL: gastrocnemius lateralis; SOL: soleus; TA: tibialis anterior; EMG-RMS: root mean square.