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# Massage induces an immediate, albeit short-term, reduction in muscle stiffness

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Using ultrasound shear wave elastography, the aims of this study were: (a) to evaluate the effect of massage on stiffness of the medial gastrocnemius (MG) muscle and (b) to determine whether this effect (if any) persists over a short period of rest. A 7-min massage protocol was performed unilaterally on MG in 18 healthy volunteers. Measurements of muscle shear elastic modulus (stiffness) were performed bilaterally (control and massaged leg) in a moderately stretched position at three time points: before massage (baseline), directly after massage (follow-up 1), and following 3 min of rest (follow-up 2). Directly after massage, participants rated pain

experienced during the massage. MG shear elastic modulus of the massaged leg decreased significantly at follow-up 1 ( $-5.2 \pm 8.8\%$ ,  $P = 0.019$ ,  $d = -0.66$ ). There was no difference between follow-up 2 and baseline for the massaged leg ( $P = 0.83$ ) indicating that muscle stiffness returned to baseline values. Shear elastic modulus was not different between time points in the control leg. There was no association between perceived pain during the massage and stiffness reduction ( $r = 0.035$ ;  $P = 0.89$ ). This is the first study to provide evidence that massage reduces muscle stiffness. However, this effect is short lived and returns to baseline values quickly after cessation of the massage.

Massage is a widely used form of therapy (Goats, 1994). During major sporting events, physiotherapists spend almost half of their time delivering massage (Galloway & Watt, 2004) with the aim of achieving enhanced performance (Rinder & Sutherland, 1995), muscle recovery (Ogai et al., 2008), and prevention of injury (Moraska, 2005). The mechanisms through which these goals are obtained are proposed to be biomechanical [e.g., increased range of motion (ROM), decreased muscle stiffness], physiological (e.g., increased blood flow and muscle temperature, reduced spinal reflex excitability), and/or psychological (e.g., increased relaxation, decreased anxiety) (Weerapong et al., 2005). However, there is little compelling evidence for efficacy of this treatment modality (Weerapong et al., 2005). Further, a review on the biomechanical effects of massage reports inconsistent results between studies (Weerapong et al., 2005). This inconsistency may be due in part to the various types of massage and the duration of application. Alternatively, there may be little biomechanical effect of performing massage.

The effectiveness of massage to reduce passive muscle stiffness has been postulated (Hopper et al., 2005;

Arabaci, 2008; Huang et al., 2010) but has not been verified in humans using direct methods. There is, however, a potential for massage to reduce passive muscle stiffness. Weak but "long-lasting" cross-bridges between myosin heads and actin are spontaneously formed under resting states (Hill, 1968), contributing to increased passive muscle tension (Proske & Morgan, 1999). Mobilizing and/or stretching the muscle can decrease this resting stiffness (Axelson & Hagbarth, 2001). It is therefore possible that certain massage techniques may break these cross-bridges in a similar way, and thus be partly responsible for the increase in ROM that has been reported following massage in some studies (McKechnie et al., 2007; Arabaci, 2008). However, assessment of ROM cannot provide conclusive evidence of altered muscle stiffness. Besides the close relationship with passive muscle stiffness (Proske & Morgan, 1999; Guissard & Duchateau, 2006), ROM is also related to stretch tolerance (Magnusson et al., 1996) and neural factors [e.g., decreased spinal reflex excitability (Guissard & Duchateau, 2006)] that could also be altered by massage (Behm et al., 2013). To definitively determine if massage does reduce muscle stiffness, a

direct assessment of muscle mechanical properties is required.

Supersonic shear imaging (SSI) is a shear wave elastography technique that quantifies the shear elastic modulus (stiffness) of a localized area of tissue (Bercoff et al., 2004). SSI provides a reliable measure of muscle shear elastic modulus (Lacourpaille et al., 2012), with a linear relationship between muscle shear elastic modulus and muscle stress during passive stretching. This has been demonstrated both *in vivo* (Maisetti et al., 2012; Chernak et al., 2013; Hug et al., 2013) and *ex vivo* (Koo et al., 2013). Taking advantage of this technique, muscle slack length has also been determined on medial gastrocnemius [MG (Maisetti et al., 2012)] and on each head of biceps brachii (Lacourpaille et al., 2013). Therefore, this technique provides a unique opportunity to quantify the effect of massage on muscle stiffness.

The aims of this study were twofold: (a) to evaluate the effect of 7 min of massage (a standardized combination of effleurage, petrissage, and deep circular frictions) on stiffness of the MG muscle measured at a moderately stretched position; and (b) to determine whether this effect (if any) persists over a short period of rest. We hypothesized that massage would reduce muscle stiffness but that the effect would not persist over time.

## Methods

### Participants

Eighteen healthy volunteers (6 female; age:  $28.0 \pm 6.4$  years; height:  $176 \pm 8.1$  cm; weight:  $71.8 \pm 10.0$  kg) participated in the experiment. Participants were excluded if they had any current pain in the lower extremities, chronic ankle instability, or neurologic condition. Participants provided written informed consent prior the start of the experiment. The Institutional Medical Research Ethics Committee (The University of Queensland) approved the study, and the experiments were conducted in accordance with the Helsinki Declaration (2001).

### Measurements

An Aixplorer ultrasound scanner (version 8.2; Supersonic Imagine, Aix-en-Provence, France) coupled with a linear transducer array (4–15 MHz; SuperLinear 15-4, Vermon, Tours, France) was used in shear wave elastography mode (musculoskeletal preset). The method used to obtain the shear wave speed

( $V_s$ ) is described in detail elsewhere (Bercoff et al., 2004). Assuming a linear elastic behavior (Bercoff et al., 2004; Catheline et al., 2004), the muscle shear elastic modulus ( $\mu$ ) was calculated as follows:

$$\mu = \rho V_s^2 \quad [1]$$

where  $\rho$  is the density of muscle ( $1000 \text{ kg/m}^3$ ). Maps of the shear elastic modulus were obtained at 1 sample per second with a spatial resolution of  $1 \times 1 \text{ mm}$ .

The SSI measurements were performed at a midpoint of the length of the MG muscle belly,  $\sim 3\text{--}4 \text{ cm}$  medial of the division between medial and lateral gastrocnemius. B-mode images were used to determine the MG fiber orientation. When several fascicles could be observed without interruption across the image (Blazevich et al., 2006), the probe location was traced on the skin and was kept the same for all the measurements within each participant. Measurements of MG shear elastic modulus (stiffness) were performed before massage (baseline), immediately after massage (follow-up 1), and after 3 min of rest following the last measurement of follow-up 1 (follow-up 2) on both the massaged and non-massaged (control) leg (Fig. 1). No precondition of the limbs was performed before the investigation began. During the experimental period, participants laid prone on a padded treatment plinth with legs supported to  $\sim 5 \text{ cm}$  above the ankles and their feet overhanging the end of the plinth. For each SSI measurement, the ankle of the participant was passively supported at  $10^\circ$  of plantarflexion ( $0^\circ = \text{foot perpendicular to the leg}$ ) by moving the plinth such that both feet were gently pressed against the wall. This ankle angle was chosen such that the MG was moderately stretched and thus developed passive tension (note that muscle stress is null if the muscle-tendon unit is slack). The slack length of the MG occurs at about  $-25^\circ$  of plantarflexion (Maisetti et al., 2012; Hug et al., 2013). Therefore,  $10^\circ$  of plantarflexion ensured that the muscle-tendon unit was moderately stretched for all the individuals. Between each measurement, the ankles were released to their resting position, which was more plantar flexed than the measurement position.

The muscle shear elastic modulus was measured for 10 s (10 values were recorded at 1 sample per second) and this was repeated three times for each leg and each time point (i.e., baseline, follow-up 1, follow-up 2). During the massage and the measurements, participants were instructed to remain “as relaxed as possible.” Muscle shear elastic modulus was measured from both legs in a randomized order, except immediately after massage where the massaged leg was always measured before the non-massaged leg. This was done because previous research (Behm et al., 2013) and pilot data provided some evidence that the effect of massage disappears rapidly upon cessation of the massage.

Immediately after the massage intervention, the participant rated the level of pain experienced during the massage on a numerical rating scale. The scale was anchored with “no pain” at 0 and “worst imaginable pain” at 10.

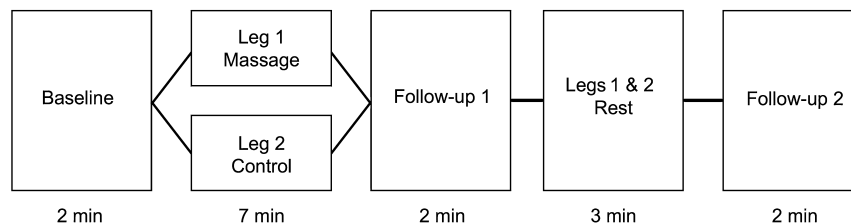


Fig. 1. Protocol of the study with the three time points for measurements. Baseline was measured before massage, follow-up 1 was measured immediately after massage, and follow-up 2 was measured after 3 min of rest following the last measurement of follow-up 1.

## Intervention

The massage intervention lasted for 7 min and was delivered to one lower leg (counterbalanced order) by an Australian registered physiotherapist with 3 years of experience (L. H.). It consisted of four phases in the following order: 2 min of effleurage, 2 min of petrissage, 2 min of deep circular friction, and 1 min of effleurage. Effleurage consisted of deep stroking movements over the skin with a smooth continuous motion (Cassar, 1999; Lowe, 2009). Petrissage consisted of compressing the tissues between the fingers of one hand and the thumb of another while lifting the soft tissues off the underlying structures (Cassar, 1999). Deep circular friction was applied using the fingertips and thumb to mobilize the superficial structures (e.g., MG) in relation to the deep structures (e.g., soleus, tibialis posterior) (Lowe, 2009). During effleurage the whole calf was treated, and during the deep friction and petrissage phases the massage focused on the area of measurement. Each phase of the massage was timed and efforts were made to keep the pressure similar between participants, and comparable to what would be used in a sports setting post exercise. During the massage, the ankle angle was in resting position (feet overhanging the foot of the plinth, as described above). After the SSI measurements at follow-up 1, the participants lay prone with their ankles in resting position during 3 min before follow-up 2.

## Data analysis

The data processing was blinded (the experimenter was not aware of the condition/side when viewing the images) and performed using Matlab (The Mathworks, Natick, Massachusetts, USA). SSI recordings were exported from the Aixplorer's software in "avi" format and sequenced in "jpeg." Image processing converted the colored map into shear elastic modulus values. First, a rectangular region of interest (ROI) was selected over the largest muscular region available on the shear elastic modulus map, excluding aponeurosis. The mean area of the ROI was  $\sim 2.5 \text{ cm}^2$ . Then the ROI within each map was inspected for artifacts or loss of shear wave data (black spots in the image). If artifacts were present in any of the images to be analyzed within a measurement (i.e., 10-s movie), the ROI was reduced in size to remove the area of artifact from all images within that measurement. Then, the shear elastic modulus was averaged over the middle 8 s (eight values) so that one representative value was obtained for each collection point. Note that the variability over these eight values was low (coefficient of variation ranged from  $1.6 \pm 0.9$  to  $2.2 \pm 1.5\%$  depending on the leg/time point).

## Statistics

One participant was unable to fully relax during the measurement of the non-massaged leg during the baseline condition (about 50% stiffer than values measured during follow-ups 1 and 2). Therefore, this participant was excluded from data analysis. All statistical analyses were performed using Statistica (StatSoft, Tulsa, Oklahoma, USA). Data distributions consistently passed the Kolmogorov–Smirnov normality test and thus all data were reported as mean  $\pm$  SD.

First, the intra-session repeatability of the shear elastic modulus measurements was assessed for each leg over the three baseline (before massage) measurements by calculating the intraclass correlation coefficient (ICC) and standard error of measurement (SEM). The potential of time-dependent change in shear elastic modulus over the three consecutive measurements performed within each time point (i.e., baseline, follow-up 1, and follow-up 2) for each leg (i.e., control and massaged leg) was also tested using separate repeated measures analyses of variance (ANOVAs) (i.e., six ANOVAs, with measurements 1, 2, 3 as the dependent

variable). Then a two-way repeated measures ANOVA was performed, with leg (control and massaged leg) and time (baseline, follow-up 1, and follow-up 2) as within-subject factors. Post-hoc analyses were performed using the least significant difference (LSD) test.  $P$  values  $< 0.05$  were considered significant. The relationship between pain ratings or depth of the ROI (respectively) and change in stiffness was tested at follow-up 1 using Pearson's correlation coefficient. Finally, Cohen's  $d$  values (standard deviation of the difference used as the standardizer) are reported as measures of effect size, with 0.2, 0.5, and 0.8 as small, moderate, and large effects, respectively (Cohen, 1988).

## Results

### Muscle shear elastic modulus

Excellent intra-session reliability was found over the three measurements performed during baseline for both the control (ICC = 0.98, SEM = 0.14 kPa) and massaged (ICC = 0.96, SEM = 0.22 kPa) legs. In addition, there was no effect of time on the three measurements for either leg and any time point considered ( $P$  values ranged from 0.15 to 0.89). Consequently, data were averaged over the three measurements.

Figure 2 depicts a typical example of the shear elastic modulus map measured during baseline, follow-up 1, and follow-up 2. A significant leg  $\times$  time interaction

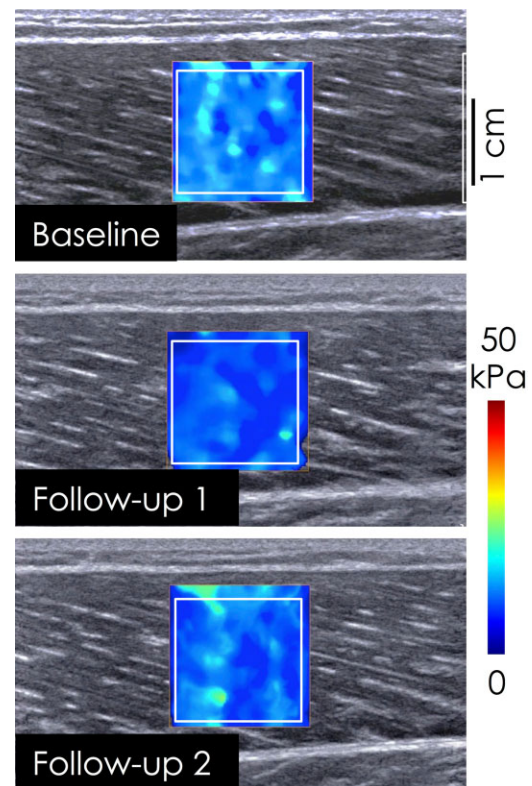


Fig. 2. Individual example of shear elastic modulus maps obtained at baseline, follow-up 1, and follow-up 2. The map of shear elastic modulus is superposed onto the B-mode image, with the color scale depicting graduation of shear elastic modulus (scale in kPa). To obtain a representative value, the shear elastic modulus (in kPa) was averaged over the region of interest (in white).



( $P = 0.037$ ) was found on the MG shear elastic modulus. There was no significant difference between legs at baseline ( $P = 0.47$ ). MG shear elastic modulus of the massaged leg was significantly lower immediately after massage (follow-up 1:  $10.3 \pm 2.6$  kPa) compared with both baseline ( $11.0 \pm 3.1$  kPa,  $P = 0.019$ ) and following rest (follow-up 2:  $10.9 \pm 2.8$  kPa;  $P = 0.031$ ) (Fig. 3). Individual data, including baseline values, are depicted in Fig. 4. This decrease in muscle shear elastic modulus compared with baseline ( $-5.2 \pm 8.8$  %) is considered a “moderate” effect ( $d = -0.66$ ). No significant difference was found between baseline and follow-up 2 ( $P = 0.83$ ,

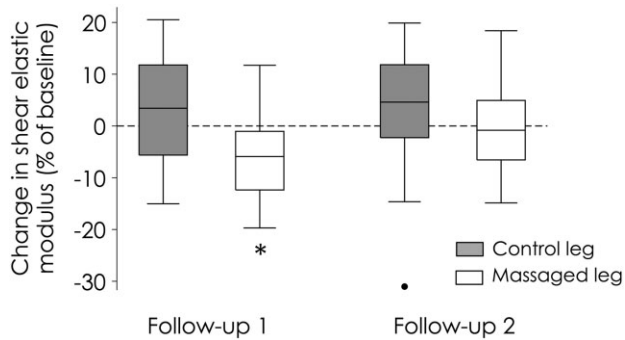


Fig. 3. Change in muscle stiffness (shear elastic modulus). Changes observed for both the massaged leg and the control leg are expressed in percentage of their baseline values. Error bars denote the 95% confidence interval; box denotes the 25th–75th percentiles with the median. The dot indicates an outlier. The asterisk indicates that the change to baseline is significant based on the statistical analysis performed on raw data and presented in the Results section.

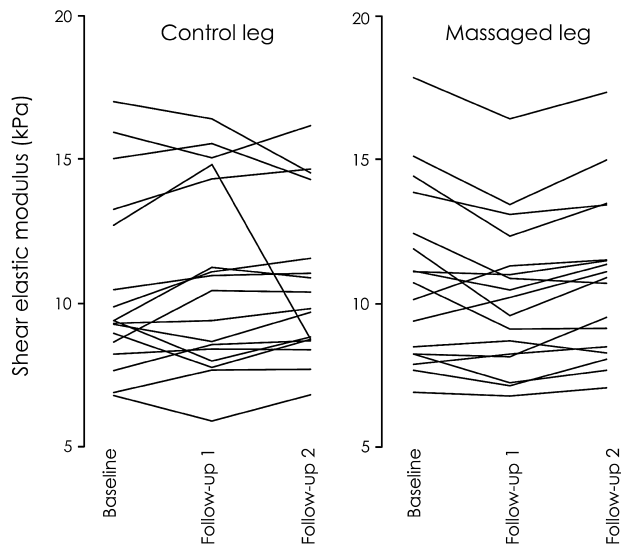


Fig. 4. Individual data of change in muscle stiffness. The shear elastic modulus (kPa) measured during baseline and two follow-up periods are shown for both the control (left) and massaged (right) legs. Note that the variability between the three time points is higher for the control leg of one participant (between follow-ups 1 and 2). Statistics were performed with (data reported in the article) and without this participant (data not reported) and the results were the same.

$d = -0.06$ ). No significant difference was found for any time points in the control leg (baseline:  $10.5 \pm 3.1$  kPa, follow-up 1:  $10.8 \pm 3.2$  kPa, follow-up 2:  $10.6 \pm 3.2$  kPa;  $P$  values ranged from 0.16 to 0.27). There was no relationship between the depth of the measurement (i.e., ROI) and the amount of decrease in muscle stiffness ( $r = 0.13$ ;  $P = 0.62$ ).

### Pain ratings

The mean level of pain experienced during the massage as rated by the participants immediately after massage was  $1.3 \pm 1.6/10$ . There was no correlation between rated pain level and reduction in shear elastic modulus for the massaged leg at follow-up 1 ( $r = 0.035$ ,  $P = 0.89$ ).

### Discussion

Taking advantage of a shear wave elastography technique (SSI), this is the first study to quantify the effect of massage on muscle stiffness in humans. Consistent with our hypothesis, 7 min of massage decreased muscle stiffness. This effect did not persist after a short rest period.

### Possible mechanisms to explain decrease in muscle stiffness

There can be several explanations for the observed short-term reduction in muscle stiffness following massage. First, there might be a decrease in motoneuron excitability as the result of a greater general sense of relaxation (Fujisawa et al., 2011) and/or a local reflex inhibition within the massaged limb (Morelli et al., 1990; Goldberg et al., 1992; Dishman & Bulbulian, 2001; Behm et al., 2013). However, the participants were instructed to remain “as relaxed as possible” throughout the testing period, and therefore the massaged muscle (and the contralateral non-massaged muscle) was likely to be myoelectrically silent and insensitive to a decrease in spinal/cortical excitability. Consequently, it is unlikely that even a local decrease in motoneuron excitability may explain the observed decrease in muscle stiffness.

Second, mechanical effects might explain the reduction in stiffness after massage. By applying pressure and stretching to the underlying muscle tissue, it is possible that massage breaks the stable cross-bridges between the actin and myosin filaments that are spontaneously formed when muscles are at rest (Hill, 1968; Proske & Morgan, 1999). This is in line with a previous study showing a decrease in passive torque resistance during wrist dorsiflexion after mechanical agitation [i.e., 10- to 15-s massage, vibration, rapid flapping of the hand (Axelson & Hagbarth, 2001)]. The gradual reattaching of the filaments that occur after breakage (Morgan et al., 1984) is likely to start immediately after massage has ceased, accounting for the short duration of stiffness reduction.

Third, it is possible that muscle stiffness decreased as a result of increased intramuscular temperature. Indeed, 5 minutes of massage of the vastus lateralis has been shown to increase intramuscular temperature by 2 °C at 1.5 cm depth (Drust et al., 2003). As *ex vivo* studies suggested that muscle shear elastic modulus is dependant on muscle temperature, with a decrease rate of about  $-2\% \text{ }^{\circ}\text{C}^{-1}$  (Sapin-de Brosse et al., 2010), this could account for, at least in part, the reduction in muscle stiffness observed in the present study. Although possible, we postulate that this cannot be the main explanation for the findings in the present study. This is because there was no relationship between the depth of the measurement (i.e., ROI), which influences the rate of increased temperature (Drust et al., 2003), and the amount of decrease in muscle stiffness ( $r = 0.13$ ).

Finally, it is likely that neither of the proposed mechanisms (i.e., breaking of resting cross-bridges and increase in intramuscular temperature) work in isolation, but instead their combined effect is responsible for the observed decrease in muscle stiffness at a moderately stretched position.

### Methodological considerations

The experimenter taking the SSI measurement was aware which leg was massaged (this was unavoidable due to the potential for a slight increase in temperature/redness of the region massaged). However, it is unlikely that this influenced the measurements. In fact, because SSI uses ultrasonic focused beams to generate mechanical vibration sources inside the tissues without external mechanical vibration, the measurement is theoretically not affected by small changes of the pressure between the probe and the skin. This awareness would have been more problematic for the processing where the experimenter had to choose the ROI. However, as mentioned in the Methods section, the data processing was blinded.

The intra-session reliability of the three baseline measurements was very high and very close to values reported previously for the same muscle (Lacourpaille et al., 2012). Consequently, the effect of massage (classified as “moderate”) is much greater than the variability of the measurements making us confident that this effect is real.

It was not possible within the current protocol to objectively confirm that the test muscle was electrically silent. This is because surface electromyography electrodes would have needed to be placed immediately above the region to be massaged and measured. However, it is well accepted that resting muscles are electrically silent in healthy participants. It is thus a reasonable assumption of this study that the muscles were electrically silent during the measurement periods.

Pain could be argued to be one factor that may influence the effect of massage. If a massage is experienced as painful, the participant may have difficulties relaxing,

and therefore may voluntarily or involuntarily increase the activity in their muscles. Muscle activation (whether voluntary or spinally mediated) is associated with active bindings between myosin and actin filaments. Therefore, it is possible that the presence of pain could reduce the effectiveness of massage at decreasing muscle stiffness. However, pain induced by the massage in the present study was low, and there was no relationship between pain and the reduction in stiffness observed in the massaged leg. Thus, we do not believe that the presence of moderate pain in some individuals influenced the results.

We have demonstrated that massage decreases muscle stiffness in healthy participants. This finding cannot be generalized to individuals with muscle pathology/injury, and is limited to the massage protocol used. However, we argue that it is likely that the effect of massage would be greater if applied to a muscle with abnormally increased stiffness (e.g., after eccentric exercise or in painful or spastic muscles). Experimental evidence from animal studies suggests that mechanical stimulation, replicating deep effleurage, can restore the viscoelastic properties of muscles after exercised muscle injuries to a greater extent than merely rest (Haas et al., 2012). This possibly indicates a more profound and/or a persistent effect of massage on injured tissue. Regarding the massage technique used, the level of pressure applied during massage (petrissage) of the calf can affect the amplitude of local reflex inhibition within the massaged limb (with increased pressure having a larger effect) (Goldberg et al., 1992). However, tapotement (percussive hacking) and petrissage (kneading) of calf muscles increase ankle ROM to a similar degree (McKechnie et al., 2007). We contend that the impact of massage techniques on the efficacy of massage is likely to be dependent on the measured outcome. Thus, future investigations are needed to determine which massage technique, or combination of techniques, is the most effective at reducing muscle stiffness. Finally, the results from this study may not be immediately inferred to other muscles, as within-muscle transmission of the mechanical load associated with massage may depend on muscle architecture. Therefore, the effect of massage may differ between muscles.

### Perspectives

SSI is a valid and reliable technique to quantify muscle stiffness (Lacourpaille et al., 2012). Given that it is a noninvasive and easy to use technique, it may provide a suitable assessment of the effectiveness of massage in reducing muscle stiffness in multiple settings. There is, however, a need to couple the findings from the present study on a mechanical effect of significant muscle stiffness reduction to a more functional outcome such as ROM or torque during passive stretching. Our study demonstrates that the functional consequence of the decrease in stiffness following massage is likely to be

limited considering the very short time span of the mechanical effect. Further research is now required to investigate the effect of massage on muscle stiffness, and its functional consequence, in a context of abnormal increase stiffness (e.g., following a bout of eccentric exercise or with pain).

**Key words:** Shear elastic modulus, tension, calf, elastography.

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## References

- Arabaci R. Acute effects of pre-event lower limb massage on explosive and high speed motor capacities and flexibility. *J Sports Sci Med* 2008; 7 (4): 549–555.
- Axelsson HW, Hagbarth KE. Human motor control consequences of thixotropic changes in muscular short-range stiffness. *J Physiol* 2001; 535 (Pt 1): 279–288.
- Behm DG, Peach A, Maddigan M, Aboodarda SJ, DiSanto MC, Button DC, Maffiuletti NA. Massage and stretching reduce spinal reflex excitability without affecting twitch contractile properties. *J Electromyogr Kinesiol* 2013; 23 (5): 1215–1221.
- Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. *IEEE Trans Ultrason Ferroelectr Freq Control* 2004; 51 (4): 396–409.
- Blazeovich AJ, Gill ND, Zhou S. Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. *J Anat* 2006; 209 (3): 289–310.
- Cassar MP. Handbook of massage therapy: a complete guide for the student and professional massage therapist. Oxford: Butterworth-Heinemann, 1999: 222.
- Catheline S, Gennisson JL, Delon G, Fink M, Sinkus R, Abouelkaram S, Culioli J. Measuring of viscoelastic properties of homogeneous soft solid using transient elastography: an inverse problem approach. *J Acoust Soc Am* 2004; 116 (6): 3734–3741.
- Chernak LA, DeWall RJ, Lee KS, Thelen DG. Length and activation dependent variations in muscle shear wave speed. *Physiol Meas* 2013; 34 (6): 713–721.
- Cohen J. Statistical power analysis for the behavioral sciences. Hillsdale: L. Erlbaum Associates, 1988: 567.
- Dishman JD, Bulbulian R. Comparison of effects of spinal manipulation and massage on motoneuron excitability. *Electromyogr Clin Neurophysiol* 2001; 41 (2): 97–106.
- Drust B, Atkinson G, Gregson W, French D, Binningsley D. The effects of massage on intra muscular temperature in the vastus lateralis in humans. *Int J Sports Med* 2003; 24 (6): 395–399.
- Fujisawa R, Kimura J, Taniguchi S, Ichikawa H, Hara M, Shimizu H, Iida H, Yamada T, Tani T. Effect of volitional relaxation and motor imagery on F wave and MEP: do these tasks affect excitability of the spinal or cortical motor neurons? *Clin Neurophysiol* 2011; 122 (7): 1405–1410.
- Galloway SD, Watt JM. Massage provision by physiotherapists at major athletics events between 1987 and 1998. *Br J Sports Med* 2004; 38 (2): 235–236, discussion 237.
- Goats GC. Massage—the scientific basis of an ancient art: part 1. The techniques. *Br J Sports Med* 1994; 28 (3): 149–152.
- Goldberg J, Sullivan SJ, Seaborne DE. The effect of two intensities of massage on H-reflex amplitude. *Phys Ther* 1992; 72 (6): 449–457.
- Guisard N, Duchateau J. Neural aspects of muscle stretching. *Exerc Sport Sci Rev* 2006; 34 (4): 154–158.
- Haas C, Best TM, Wang Q, Butterfield TA, Zhao Y. In vivo passive mechanical properties of skeletal muscle improve with massage-like loading following eccentric exercise. *J Biomech* 2012; 45 (15): 2630–2636.
- Hill DK. Tension due to interaction between the sliding filaments in resting striated muscle. The effect of stimulation. *J Physiol* 1968; 199 (3): 637–684.
- Hopper D, Deacon S, Das S, Jain A, Riddell D, Hall T, Briffa K. Dynamic soft tissue mobilisation increases hamstring flexibility in healthy male subjects. *Br J Sports Med* 2005; 39 (9): 594–598, discussion 598.
- Huang SY, Di Santo M, Wadden KP, Cappa DF, Alkanani T, Behm DG. Short-duration massage at the hamstrings musculotendinous junction induces greater range of motion. *J Strength Cond Res* 2010; 24 (7): 1917–1924.
- Hug F, Lacourpaille L, Maisetti O, Nordez A. Slack length of gastrocnemius medialis and Achilles tendon occurs at different ankle angles. *J Biomech* 2013; 46 (14): 2534–2538.
- Koo TK, Guo JY, Cohen JH, Parker KJ. Relationship between shear elastic modulus and passive muscle force: an ex-vivo study. *J Biomech* 2013; 46 (12): 2053–2059.
- Lacourpaille L, Hug F, Bouillard K, Hogrel JY, Nordez A. Supersonic shear imaging provides a reliable measurement of resting muscle shear elastic modulus. *Physiol Meas* 2012; 33 (3): N19–N28.
- Lacourpaille L, Hug F, Nordez A. Influence of passive muscle tension on electromechanical delay in humans. *PLoS ONE* 2013; 8 (1): e53159.
- Lowe WW. Orthopedic massage: theory and technique. Oxford: Elsevier Health Sciences, 2009: 320.
- Magnusson SP, Simonsen EB, Aagaard P, Sorensen H, Kjaer M. A mechanism for altered flexibility in human skeletal muscle. *J Physiol* 1996; 497 (Pt 1): 291–298.
- Maisetti O, Hug F, Bouillard K, Nordez A. Characterization of passive elastic properties of the human medial gastrocnemius muscle belly using supersonic shear imaging. *J Biomech* 2012; 45 (6): 978–984.
- McKechnie GJ, Young WB, Behm DG. Acute effects of two massage techniques on ankle joint flexibility and power of the plantar flexors. *J Sports Sci Med* 2007; 6 (4): 498–504.
- Moraska A. Sports massage. A comprehensive review. *J Sports Med Phys Fitness* 2005; 45 (3): 370–380.
- Morelli M, Seaborne DE, Sullivan SJ. Changes in h-reflex amplitude during massage of triceps surae in healthy subjects. *J Orthop Sports Phys Ther* 1990; 12 (2): 55–59.
- Morgan DL, Prochazka A, Proske U. The after-effects of stretch and fusimotor stimulation on the responses of primary

## Effect of massage on muscle stiffness

- endings of cat muscle spindles. *J Physiol* 1984; 356: 465–477.
- Ogai R, Yamane M, Matsumoto T, Kosaka M. Effects of petrissage massage on fatigue and exercise performance following intensive cycle pedalling. *Br J Sports Med* 2008; 42 (10): 834–838.
- Proske U, Morgan DL. Do cross-bridges contribute to the tension during stretch of passive muscle? *J Muscle Res Cell Motil* 1999; 20 (5–6): 433–442.
- Rinder AN, Sutherland CJ. An investigation of the effects of massage on quadriceps performance after exercise fatigue. *Complement Ther Nurs Midwifery* 1995; 1 (4): 99–102.
- Sapin-de Brosse E, Gennisson JL, Pernot M, Fink M, Tanter M. Temperature dependence of the shear modulus of soft tissues assessed by ultrasound. *Phys Med Biol* 2010; 55 (6): 1701–1718.
- Weerapong P, Hume PA, Kolt GS. The mechanisms of massage and effects on performance, muscle recovery and injury prevention. *Sports Med* 2005; 35 (3): 235–256.