`Research article`

Effects of Foam Rolling Duration on Tissue Stiffness and Perfusion: A Randomized Cross-Over Trial

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Abstract

Despite its beneficial effects on flexibility and muscle soreness, there is still conflicting evidence regarding dose-response relationships and underlying mechanisms of foam rolling (FR). This study aimed to investigate the impact of different FR protocols on tissue perfusion and tissue stiffness. In a randomized crossover trial, two FR protocols (2x1 min, 2x3 min) were applied to the right anterior thigh of twenty healthy volunteers (11 females, 25 ± 4 years). Tissue perfusion (near infrared spectroscopy, NIRS) and stiffness (Tensiomyography, TMG and Myotonometry, MMT) were assessed before and after FR application. Variance analyses revealed a significant interaction of FR duration and tissue perfusion ($F_{[1,19]}$ = 7.098, p = 0.015). Local blood flow increased significantly from pre to post test ($F_{[1,19]}$ = 7.589, p = 0.013), being higher (Δ +9.7%) in the long-FR condition than in the short-FR condition (Δ +2.8%). Tissue stiffness (MMT) showed significant main effects for time ($F_{[1,19]}$ = 12.074, p = 0.003) and condition ($F_{[1,19]}$ = 7.165, p = 0.015) with decreases after short-FR (Δ -1.6%) and long-FR condition (Δ -1.9%). However, there was no time*dose-interaction ($F_{[1,19]}$ = 0.018, p = 0.895). No differences were found for TMG (p > 0.05). FR-induced changes failed to exceed the minimal detectable change threshold (MDC). Our data suggest that increased blood flow and altered tissue stiffness may mediate the effects of FR although statistical MDC thresholds were not achieved. Longer FR durations seem to be more beneficial for perfusion which is of interest for exercise professionals designing warm-up and cool-down regimes. Further research is needed to understand probable effects on parasympathetic outcomes representing systemic physiological responses to locally applied FR stimulations.

Key words: Musculoskeletal, exercise physiology, physiotherapy, relaxation, athletic training.

Introduction

Foam rolling (FR) has become a popular intervention in the fitness and health sector. Available meta-analyses suggest a beneficial impact on joint flexibility (Wilke et al., 2020) and, although with higher inconsistency, markers of performance and recovery (Behm and Wilke, 2019; Wiewelhove et al., 2019). However, despite the accumulating evidence regarding general functionality, the exact mechanisms as well as the optimal application parameters are still a matter of debate (Cheatham and Stull, 2019). To best match FR paradigms with different populations and treatment goals, understanding both is crucial (Macgregor et al., 2018a).

The strength of tissue compression and treatment duration represent two common parameters in FR. Only after application of high painful pressures, (Young et al., 2018) showed very short-lived reductions of the h reflex during FR, suggesting altered pre-synaptic transmission or alpha motoneuron excitability. More rigid FR devices have been shown to induce larger effects on flexibility and pain pressure threshold (Cheatham and Stull, 2019) than softer instruments (Grabow et al., 2018; Wilke et al., 2019). With regard to FR duration, a few studies indicate a possible dose-response-relationship for flexibility and power seems to decrease as a function of rolling duration (Phillips et al., 2021; Sullivan et al., 2013).

Despite initial evidence regarding dose-dependent adaptations in pain and flexibility, little is known yet about the impact of treatment duration on markers of tissue physiology. Sixty seconds of FR were neither enough to improve flexibility nor sufficient to alter muscle temperature or muscle stiffness (Dębski et al., 2019; Murray et al., 2016). Furthermore, a ninety seconds rolling intervention improved joint range of motion (ROM), but failed to affect shear elastic modulus as a surrogate of tissue stiffness (Nakamura et al., 2021). In contrast, a three-minute protocol with both, vibrating and non-vibrating rollers led to stiffness decreases (ultrasound shear wave elastography) in the rectus femoris, but not to the vastus muscles of the anterior thigh (Reiner et al., 2021). Finally, also using shear wave elastography, Morales-Artacho et al. (2017) observed small short-term stiffness decreases without meaningful ROM changes after a fifteen-minute FR warm-up protocol.

From a theoretical point of view, the underlying mechanisms of FR can be either of mechanical or neurophysiological origin (Beardsley and Skarabot, 2015). As FR is characterized as a form of self-massage with the pressure of the own body weight being applied to muscles and connective tissues (Macgregor et al., 2018a), the mechanisms may probably be comparable to those reported earlier for deep tissue massage techniques (Weerapong et al., 2005). Here, beside others, alterations of local perfusion and muscle stiffness have been discussed to mediate the observed effects (Casanova et al., 2018; Hotfiel et al., 2017; Macgregor et al., 2018a; Okamoto et al., 2013; Wilke et al., 2019). Stiffness appears to be of special interest, because it involves neural (Macgregor et al., 2018a) and mechanical (Baumgart et al., 2019) components. However, there is conflicting evidence about FR effects on local muscle stiffness due to the variety of used devices, applied dose-response conditions (see above), and examined

samples, e.g. participants with and without DOMS (Baumgart et al., 2019; Macgregor et al., 2018a; Martínez-Cabrera and Núñez-Sánchez, 2016; Murray et al., 2016; Schroeder et al., 2019; Schroeder et al., 2017).

In summary, based on the available literature, there is no consensus describing how long FR should be administered. Therefore, this study investigated the acute effects of a single session with FR short or long duration on tissue perfusion and stiffness. It was hypothesized that longer FR applications would show more pronounced effects on perfusion increases while more strongly decreasing stiffness.

Methods

Study design and ethics
A cross-over trial with two conditions was performed. In randomized order and with a wash-out period of one week in-between, twenty healthy adult participants completed two 1-min and two 3-min bouts of FR on the right anterior thigh (EXP). The left leg remained untreated (CON). Before and after treatment, peripheral blood flow as well as mechanomyography soft tissue and muscle stiffness were

examined in a fixed order. The two FR conditions were investigated in two subsequent weeks at the same time of the day (± 1 hour) at the same location in our laboratory in a randomized order (by lot). The randomization procedure (coin throw) was carried out by the participants themselves at their first visit and under supervision of the investigator (Figure 1). The investigator performing the statistical analysis was blinded to sequence allocation. The wash-out period was defined as one week to exclude carryover effects. All participants were asked to abstain from fatiguing exercise in the preceding 48 hours.

Approval was obtained from the local research ethics committee (AZ2017_111) and all participants provided written informed consent. The study was conducted in accordance with the guidelines of the Declaration of Helsinki including its latest modification.

Participants
An a priori sample size calculation was performed using G*Power 3.1 (University of Kiel, Germany). In order to detect clinically relevant effects (Murray et al., 2016) we chose an effect size of $f = 0.4$. We obtained a minimum
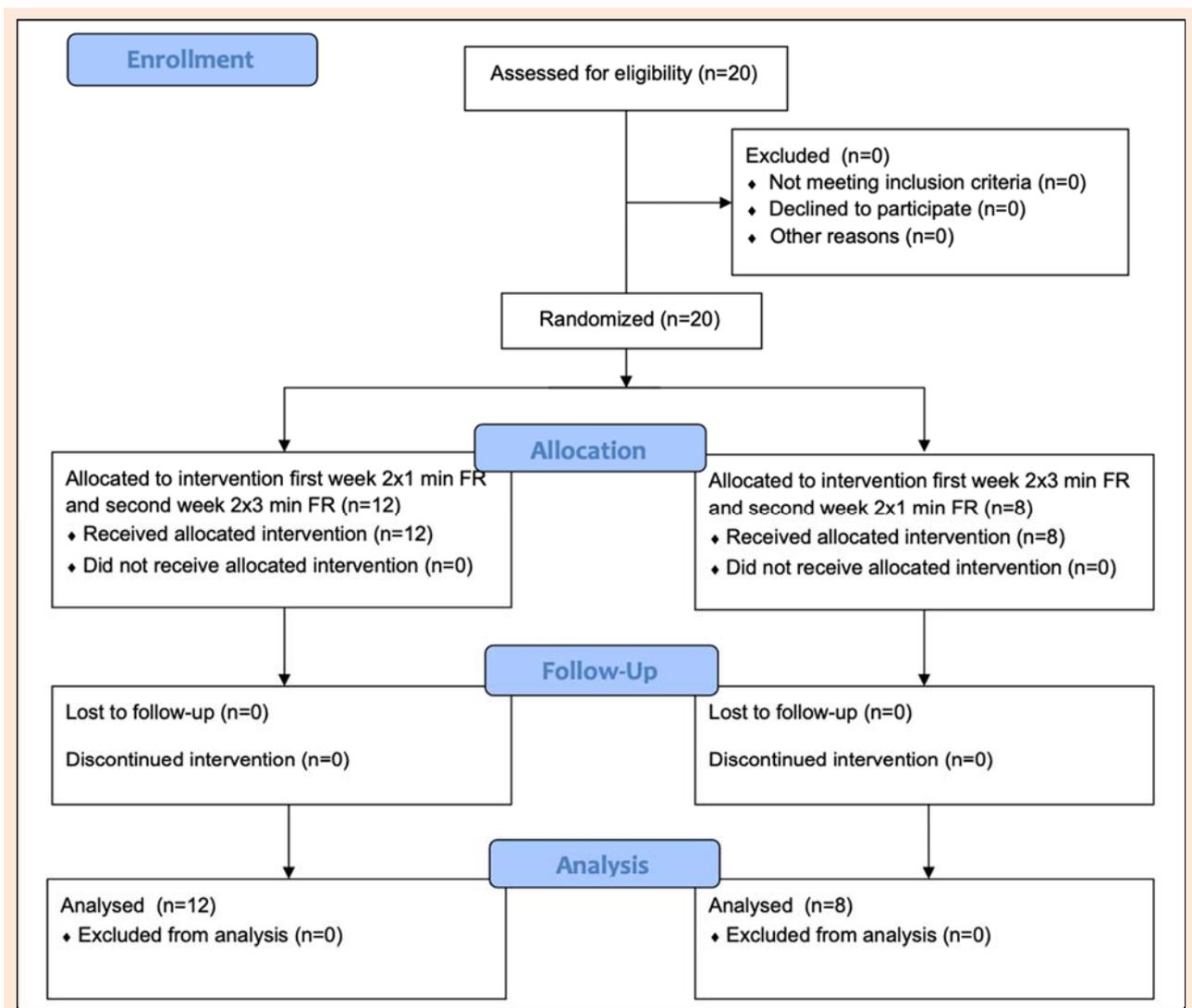

Figure 1. CONSORT flow chart.

sample size of 14 cases with a statistical test power of greater than ß = 0.93. To take account for possible drop outs, twenty healthy volunteers (11 female, 9 male) were recruited by means of local advertising (poster and word of mouth, Table 1). The volunteers were students and university staff of our institution involved in various sports or physical activities. Participants were familiar with FR techniques, but FR was not part of their regular exercise routine. Exclusion criteria were acute and chronic injuries to the musculoskeletal system, as well as pregnancy or the actual intake of pain medication.

Table 1. Sample characteristics.

	Age (y) M (SD)	Height (m) M (SD)	Mass (kg) M (SD)	BMI (kg/m²) M (SD)
Females (n=11)	24.3 (2.1)	1.73 (.08)	67.0 (9.2)	22.3 (2.0)
Males (n=9)	25.9 (4.6)	1.83 (.05)	84.4 (8.7)	25.1 (1.6)
Total (n=20)	25.0 (3.5)	1.78 (.08)	74.8 (12.4)	23.6 (2.3)

BMI *body mass index*, SD *standard deviation*, y *years*

Interventions

Depending on the randomized conditions order, the participants performed an acute bout of FR with varying duration (2x1 min vs. 2x3 min) without any prior practical session. They were instructed to adopt a prone position, self-massaging the anterior thigh with continuous strokes from the kneecap to the superior anterior iliac spine. Movements were executed at a cadence of 30 rolls per minute (controlled with a cell phone metronome application), meaning that 2 s were needed per stroke (Figure 2A). In an earlier study, using a force plate, Baumgart et al. (2019) showed the pressure during FR of the anterior thigh to amount 34% (average ground reaction force calculated for the complete roll out circle) Our FR protocol was very similar and hence, a similar pressure can be assumed. During the intervention, the participants were instructed to avoid muscular contractions of the treated muscles. The two sets (2x1 min or 2x3 min, respectively) were separated by one-minute rests. The left limb remained untreated and served as a control (Perez-Bellmunt et al., 2021). The used FR device (Black-Roll®, Bottighofen, Switzerland) had a medium hard density and a length of 30 cm with a diameter of 15 cm.

Outcomes

Outcomes were assessed pre- and post-intervention in both legs. We determined the middle of the muscle belly of the rectus femoris muscle at 50% of the distance between the anterior spina iliaca superior and the superior part of the patella following the SENIAM project recommendations (http://seniam.org/quadriceps). We controlled the muscle belly position during a voluntary isometric contraction and marked the respective spot with a skin-marker in order to keep this point constant throughout the repeated measurement protocol. At fixed order, in both, the right (EXP) prior to the left (CON) leg, we assessed peripheral blood flow at the marked spot of the anterior thigh using near-infrared spectroscopy (NIRS, required duration: 4 minutes), soft tissue stiffness at the same spot using myotonometry (MMT, 1 minute), and contractile properties of the rectus femoris

muscle at the same spot using tensiomyography (TMG, less than 2 minutes) (Figure 3).

All NIRS, MMT and TMG measurements were performed by an experienced investigator with the participants positioned laid back on an examination table with a cushion under the knees to maintain the knee angle (about 130° to 135° extended) with the leg muscles relaxed and the arms resting at the side (Figure 2).
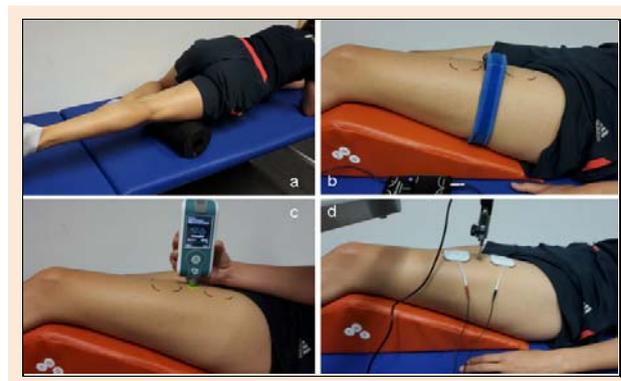

Figure 2. Foam Rolling for the right anterior thigh (a), positioning of the Near-Infrared sensor (optodes covered with a strap in order to fix the optodes and avoid scattered light) at the anterior thigh (b), tissue stiffness assessment using the MyotonPro® at the same spot of the anterior thigh (c), and muscle stiffness assessment using the TMG® (sensor tip and electrodes) again at the same spot of the anterior thigh over the rectus femoris muscle following the SENIAM recommendations (d).

Near-infrared spectroscopy

To examine peripheral blood flow dynamics, we used a simple two channel NIRS device (MediTECH Electronics Ltd., Wedemark, Germany) for bilateral measurements. The device calculates the mixed tissue saturation by measuring the oxygenated and deoxygenated erythrocytes in the tissue with arterial, venous and capillary origin (Owen-Reece et al., 1999). In brief, red light (647 nm) and infrared light (850 nm) is sent into the soft tissue of the anterior thigh at the marked spot. Reflections of the emergent light are detected by a sensor optode. Red/infrared transmitter and detector optodes had a distance of 3 cm. While oxygenated and deoxygenated bloods differ markedly in the red light wavelength spectrum, they hardly differ in the infrared light wavelength spectrum (Owen-Reece et al., 1999). These absorption differences were used to calculate a red-infrared ratio (R/IR ratio). The more oxygen the more red will be reflected and the higher the R/IR ratio. The signals were collected using two channels (red, infrared) with a sampling rate of 256 Hz during a time window of two minutes for calculations of the R/IR ratio with a system's specific software (Biograph Infiniti, MediTech Electronics Ltd., Wedemark, Germany). Heart beat or respiration interferences were low pass filtered (0.3 Hz) by the software. Due to an early phase signal shift after the sensor application, the oxygenated perfusion was expressed as the R/IR ratio's mean of the interval between the 60th and the 120th second of the data collection. To avoid scattered light artefacts, the room was darkened for NIRS measurements and the sensor was covered with a customized tensor bandage (Figure 2B). Reliability was reported to be acceptable
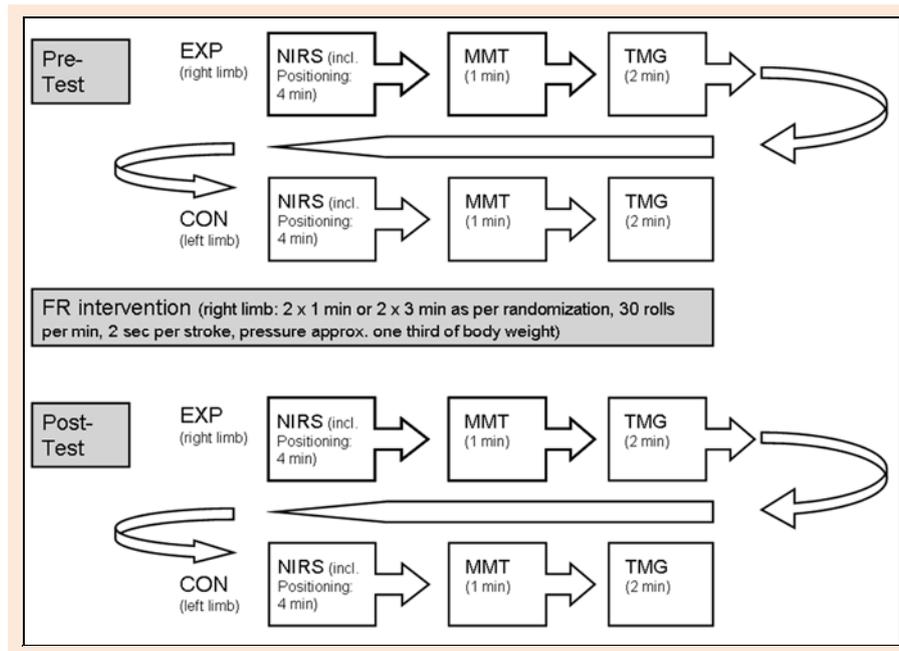
Figure 3. Data assessment schedule flow-chart.

(ICC 0.69 - 0.84) (Kell et al., 2004). In our own laboratory, we determined similar coefficients (ICC3.1 0.71 - 0.74). The ICC calculated from the two pre-tests of our sample (n = 20) was 0.75 with an MDC of 33.1 AU (arbitrary units, R/IR ratio). The measurements including the individual's positioning, sensor application and covering, software handling and data export took about 4 minutes in total for one limb.

Myotonometry
The viscoelastic properties of the anterior thigh soft tissue were assessed using a hand-held MMT device (Myo-tonPro®, Myoton Ltd. Tallinn, Estonia) (Figure 2 C). MMT working principles were described earlier (Bailey et al., 2013; Ditroilo et al., 2011). The examination device was placed orthogonal to the surface of the skin with a defined preload (0.18 N). In contrast to earlier versions, the MyotonPro® device provided a software-controlled feedback for the examiner indicating the correct preload and testing end orientation. The MMT generated a short (15 ms) mechanical stimulus (0.4 N) in order to cause a soft tissue deformation. After a quick-release the testing end recorded (3200 Hz) the damped oscillations of the deformed soft tissue by a 3-axis digital acceleration sensor (Bailey et al., 2013). We used the triple scan mode (3 stimuli, 1s intervals) that displayed means of three measurements and its coefficient of variation. Measures were accepted, when coefficients of variation were lower than 3% (Mullix et al., 2012). The properties of the deformed soft tissue can be characterized as its viscoelastic stiffness (S), with higher values indicating a greater stiffness. S (N/m) was calculated as the ratio between the force applied (the product of the acceleration of the first oscillation and the mass of the testing probe) and the tissue's deformation calculated as the second mathematical differentiation from the recorded acceleration maximum (S = $a_{max} \times m/\Delta l$). MMT measures for the respective limb were assessed

within less than one minute, which was possible because the standardized subject's positioning was already adopted. The system's validity for tissue stiffness analyses was reported earlier (Pruyn et al., 2016). For the rectus femoris muscle, reliability was demonstrated earlier as being good to excellent with ICCs ranging between 0.72 and 0.87 (Mullix et al., 2012). In our own laboratory, we determined a day-to-day intra-examiner reliability with ICC3.1 coefficients higher than 0.89. The ICC calculated from the two pre-tests of our sample (n = 20) was 0.89 with an MDC of 31.5 N/m.

Tensiomyography
Contractile properties of the rectus femoris muscle were assessed using tensiomyography (TMG®, Lubljana, Slovenia) (Figure 2 D). According to the protocol described earlier, a high-precision (4 μm) digital displacement sensor tip with a prefixed tension of 0.17 N/m (TMG-BMC, Ljubljana, Slovenia) was positioned perpendicular to the surface at the marked spot of the muscle belly to detect the maximum radial displacement (Dm) as a spatial parameter of the muscle deformation. Dm is related to the actual muscle tone at a given state of muscle hypertrophy. Lower values indicate higher muscle stiffness (Macgregor et al., 2016). Higher values are supposed to represent a reduced stiffness (Macgregor et al., 2018b). Muscle contractions were triggered by repeated electrical stimulations (1 ms, starting from 20 mA and increasing step by step with increments of about 15 mA up to a maximum 100 mA) until the maximum displacement was achieved (varying inter-individually between 65 mA und 100 mA). Stimulations were conducted using a specific stimulator (TMG-S2) and software (TMG-OK 3.0) and were separated by 10 s rest intervals to minimize the effects of fatigue or potentiation (Wilson et al., 2018). Electrodes (5×5 cm) were positioned with their center points 5 cm distal and proximal to the sensor. Sensor and electrode positions were marked on the

Table 2. Descriptive statistics and effect analyses for the pre- and post-test values of Near-Infrared Spectroscopy (NIRS), Tensiomyography (TMG), and Myotonometry (MMT) for both dose conditions (2x1 min, 2x3 min) of foam rolling for the right (EXP) and for the left (CON) anterior thigh.

| | | | dose 2x1 min | | | | dose 2x3 min | | | | main effects | | | | interaction | |
| | | | pre | | post | | pre | | post | | dose | | time | | dose x time | |
			M	(SD)	M	(SD)	M	(SD)	M	(SD)	F[1, 19]	(p) η²part	F[1, 19]	(p) η²part	F[1, 19]	(p) η²part
NIRS	R/IR ratio (AU)	EXP (right)	118.4	(17.5)	121.0#	(16.1)	117.9	(29.0)	128.0#	(26.0)	0.646	(0.432) 0.033	7.589	(0.013)* 0.285	7.098	(0.015)* 0.272
		CON (left)	115.5	(13.8)	113.6	(14.2)	115.9	(28.5)	118.5	(27.5)	0.273	(0.608) 0.014	0.048	(0.829) 0.003	3.192	(0.090) 0.144
TMG	Dm (mm)	EXP (right)	8.9#	(2.8)	8.8#	(3.3)	8.8#	(2.8)	9.0	(2.4)	0.002	(0.965) <0.001	0.063	(0.805) 0.003	0.879	(0.360) 0.044
		CON (left)	7.3	(3.0)	7.8	(3.0)	7.8	(2.9)	8.3	(2.9)	2.505	(0.130) 0.116	2.558	(0.126) 0.119	0.003	(0.954) <0.001
MMT	S (N/m)	EXP (right)	242.6	(32.3)	238.6	(31.6)	231.2	(35.4)	226.8	(35.5)	7.165	(0.015)* 0.274	12.074	(0.003)* 0.389	0.018	(0.895) 0.001
		CON (left)	247.8	(38.7)	243.7	(36.7)	236.3	(38.0)	235.9	(38.2)	5.266	(0.033)* 0.217	1.763	(0.200) 0.085	0.956	(0.341) 0.048

* statistically significant ANOVA effect; # statistically significant difference between EXP and CON limb at any single time point of measurement (t-test); M=mean; SD= standard deviation; R/IR ratio=red/infrared ratio mean value of the interval between the 60th and the 120th second; Dm muscle belly displacement; S tissue stiffness

skin (Macgregor et al., 2016; Wilson et al., 2018). At the beginning of the data collection, if necessary, the sensor position was slightly adjusted to achieve the maximal response amplitude (Ditroilo et al., 2011; Macgregor et al., 2016). The average of the last two twitch displacement-time curves with no further increases of the Dm level were used to determine the Dm values. Data assessment for one limb took less than two minutes. Dm reliability of quadriceps measurements was reported as ICCs of higher than 0.91 (Tous-Fajardo et al., 2010). In our own laboratory, we determined reliability as ICC3.1 coefficient of up to 0.92. The ICC calculated from the two pre-tests of our sample (n=20) was 0.81 with an MDC of 3.4 mm.

Statistical Analyses

Data were described as means (M) and standard deviations (SD). Normal distribution was verified by means of the Shapiro Wilk test. A repeated-measures ANOVA for a two-factor (2x2) data model was conducted separately for each limb (EXP, CON) to reveal main effects and interactions (pre-post x dose condition). Post-hoc, pre-post changes and differences of dose-dependent changes were identified using paired t-tests. In order to demonstrate whether the observed changes were clinically relevant, the minimal detectable change (MDC) was calculated (MDC = SEM x 1.96 x $\sqrt{2}$, with SEM = SD x $\sqrt{[1-ICC]}$). Additionally, paired t-tests and the corresponding effect size (dz) were calculated in order to analyze mean differences between the right and the left limb separately at any point of measurements. A point-biserial correlation was calculated in order to rule out any sex influence on pre-post outcome changes. P-values ≤ 0.05 were considered as statistically significant.

Results

The point-biserial correlation analyses revealed minimal coefficients ranging from 0.01 to 0.12 (p = .612 to .982) between sex and the pre-post changes in any of the analyzed outcomes, except for the NIRS R/IR ratio at the 2x3 min condition, which was either small and non-significant but a little higher (r = 0.34, p = .137). Thus, there was no need to conduct sex-specific analyses.

For local perfusion (NIRS), we found a significant interaction with pronounced increases for the longer FR condition ($F_{[1,19]}$ = 7.098, p = 0.015). Additionally, a significant main effect occurred for time ($F_{[1,19]}$ = 7.589, p = 0.013), demonstrating increases from pre to post measures in both durations: Δ+2.8% (2.55 AU, $t_{[19]}$ = 0.889, p = .385, dz = 0.20) after 2x1 min FR, and Δ+9.7% (10.04 AU, $t_{[19]}$ = 4.043, p = .001, dz = 0.90) after 2x3 min FR. For the control limb, there were no significant interactions or main effects. Direct comparisons between the EXP and CON limb revealed significant differences at both post-test measurements (2x1 min $t_{[19]}$ = 2.757, p= 0.013, dz = 0.62; 2x3 min $t_{[19]}$ = 4.822, p < 0.001, dz = 1.08) implying no significant baseline differences at the pre-test measurements (Table 2).

With regard to muscle stiffness as measured with TMG, we neither found effects for the treated (EXP) nor for the untreated leg (CON). However, there were significantly higher values for Dm of the right limb before the treatment at the pre-test measurements (2x1 min: Δ+18.6%, $t_{[19]}$ = 3.689, p = 0.002, dz = 0.83; 2x3 min: Δ+10.7%, $t_{[19]}$ = 3.287, p = 0.004, dz = 0.74), as well as for the 2x1 min post-test after the treatment (Δ +6.1%, $t_{[19]}$ = 2.273, p = 0.035, dz = 0.51), but not for the post-test after 2x3 min FR (Δ +6.9%, $t_{[19]}$ = 1.635, p = 0.118, dz = 0.37) reflecting a baseline difference between limbs with reduced muscle stiffness in the rolled leg (Table 2).

There were no significant interactions for MMT measurements in the tested limbs. Yet, in both legs, we observed significant main effects for 'dose' ($F_{[1,19]} = 7.165$, $p = 0.015$; $F_{[1,19]} = 5.266$, $p = 0.033$, respectively), revealing higher values at the pre- and post-tests for the shorter 2x1 min FR dose condition for the treated limb as well as for the untreated leg, despite the randomized order of conditions. For the EXP limb, a significant time effect ($F_{[1,19]} = 12.074$, $p = 0.003$) indicated tissue stiffness decreases after 2x1 min and 2x3 min FR of, per average, -4.0 N/m (Δ-1.6%, $t_{[19]} = 2.419$, p = .026, $dz = 0.54$) and -4.4 N/m (Δ-1.9%, $t_{[19]} = 2.010$, p = .059, $dz = 0.45$). There was no time effect for the CON limb (Table 2). No significant differences were found between the EXP and the CON limb in single time point comparisons.

Despite significant global time effects for NIRS (p = .013) and MMT (p = .003) changes and some significant single time point measurement differences, none of the pre-post alterations (NIRS, MMT, and TMG) exceeded the respective MDC thresholds (33.1 AU, 31.5 N/m and 3.4 mm, respectively).

Discussion

The acute adaptations of FR as well as the optimal dose-response relationships have been an understudied topic, hitherto. Our study reports data addressing this research deficit. In order to evaluate acute effects and dose-response dependency of foam rolling on probable underlying mechanisms, the study investigated alterations of local perfusion (NIRS) and mechanomyographic parameters of muscle or tissue stiffness (TMG, MMT) after contrasting FR application durations.

In accordance with Hotfiel et al. (2017), but in contrast to Casanova et al. (2018), we found an increased local blood flow after FR. We hypothesize that the observed surge in tissue perfusion is due to a release of plasma nitric oxide which has been demonstrated to be triggered by rolling massage treatments (Okamoto et al., 2013). Interestingly, our FR intervention demonstrated general positive effects on tissue perfusion comparable to those recently reported for manually applied physical therapist massage techniques (Monteiro Rodrigues et al., 2020). The increases were significantly more pronounced for the higher FR duration (Δ +9.7% vs. Δ +2.8%), indicating a possible dose-response dependence of local perfusion in terms of the altered ratio of oxygenated and des-oxygenated blood, although MDC thresholds were not reached. Our findings may hence support earlier investigations recommending longer FR applications if greater warm-up effects are of interest (Phillips et al., 2021; Sullivan et al., 2013). Murray et al. (2016) concluded that one set of sixty seconds FR was not enough to show relevant effects on joint range of motion or probable underlying mechanisms like muscle temperature or stiffness. In our case, the FR protocol with short duration (2x 60s) was sufficient to increase blood flow (Δ +2.8%) and reduce tissue stiffness (Δ -1.6%), although these changes were partly non-significant and again remained below the MDC thresholds. This would meet roughly the recently recommended 90 to 120 seconds duration as a suitable FR application volume in order to achieve flexibility benefits for warm-up purposes (Hendricks et al., 2020; Skinner et al., 2020), although the higher-duration treatment (2x180s) additionally evoked pronounced effects on local perfusion (Δ +9.7%). The treatment volume of six minutes in total was longer than any other duration applied in previous studies (Phillips et al., 2021) and might probably be too extensive for practical application guidelines (Hendricks et al., 2020; Skinner et al., 2020).

We found no dose-dependency within our stiffness analyses, but our finding of a dose-independent decrease of tissue stiffness in terms of MMT after both FR conditions of about 1.5% to 2% was roughly in line with Baumgart et al. (2019) reporting single-session pre-post FR tissue stiffness reductions for the anterior thigh and the calf of about 2.5%. Conversely, a comparable effect was not observed for muscular stiffness in terms of TMG, although the electrically evoked muscle belly deformation is deemed to be related to muscle stiffness alterations (Macgregor et al., 2018b), and FR induced neuromuscular inhibition was hypothesized as alterations of muscles' contractile properties in terms of TMG (Macgregor et al., 2018a). Our data does not suggest locally effective neuromuscular inhibition mechanisms, although Schleip (2003) argued that neurophysiological mechanisms are more likely the reason for FR effects than purely mechanical pathways because of the immediate and short-lived character. From a physiological perspective, especially Ruffini corpuscles of superficial fascial tissues, which are known to be sensitive to tangential forces and lateral stretch stimuli according to especially slow FR may explain tissue stiffness reductions due to muscle relaxation by inhibiting sympathetic activity (Behm and Wilke, 2019). However, the time elapsed from FR to the assessment was four or five minutes longer than for the assessment of perfusion (NIRS took about 4 min) or tissue resistive torque (MMT took less than 1 min). The control limb assessment followed the assessments of the experimental limb resulting in a respective time loss. Consequently, a time period of about five to ten minutes might be enough to reset short-lived FR effects (Konrad et al., 2019). Thus, we cannot rule out this as a limiting confounder.

Apart from our analyses of probable dose-dependent TMG stiffness changes, we observed partly unexplained significant pre-test and post-test differences in the radial muscle displacement (Dm) between the experimental and the control limb - demonstrating ratios of 82% and 88% for the pre-tests before the shorter and longer FR treatment, respectively (Table 2). It may be that lateral asymmetry is typical for the non-fatigued rectus femoris muscle. For example, García-García (2015) examined lateral (dominant vs. non-dominant) and functional asymmetries of the anterior and posterior thigh muscles during cyclists' pre-seasons. He did not observe any significant asymmetries between the limbs except for the TMG-determined Dm and contraction velocity (García-García, 2015). Specifically, Dm differed markedly between the dominant and non-dominant legs in the rectus femoris muscle. Here, the measured asymmetry ratio of 82% was very

similar to our findings, while other parts of the quadriceps or the biceps femoris muscle showed no significant asymmetries (García-García, 2015). As a consequence, our finding of initially differing Dm values before FR treatments seem typical for the rectus femoris muscle.

Significant stiffness decreases after single FR sessions have been detected using passive assessments with MMT (e.g. Baumgart et al. (2019) and the present study), and shear wave elastography (Morales-Artacho et al., 2017; Reiner et al., 2021). It has to be kept in mind that the shear modulus changes were found only in one of three treated anterior thigh muscles after a 3-minute FR of the anterior thigh (Reiner et al., 2021), or after an extensive 15-minute FR protocol for the posterior thigh (Morales-Artacho et al., 2017). Furthermore, no shear elastic modulus changes were observed for the medial gastrocnemius muscle after shorter or longer FR protocols (Nakamura et al., 2021). In contrast, all studies using TMG - as an active stiffness assessment of electrically evoked involuntary isometric muscle contractions - failed to identify such effects (Martínez-Cabrera and Núñez-Sánchez, 2016; Murray et al., 2016; Schroeder et al., 2017). Interestingly, one recently published paper also using TMG-based and MMT-based muscle (Dm) and tissue (S) stiffness parameters reported findings with no significant changes in TMG stiffness but significant decreases in MMT stiffness after manually applied five minutes physiotherapist massage techniques for the lower limb calf muscles (Perez-Bellmunt et al., 2021). There was one study reporting TMG based stiffness effects after FR, but this study consisted of repeated FR sessions and the effect referred exclusively to the third of three consecutive days (Macgregor et al., 2018a). However, this effect remains ambiguous, because it was reported only for the vastus lateralis and not for the rectus femoris muscle, although the whole anterior thigh was treated. Moreover, these findings referred solely to changes of the untreated control condition but not to the FR treatment, which was comparable to earlier TMG findings after a single FR session remaining unexplained by the authors (Martínez-Cabrera and Núñez-Sánchez, 2016).

The findings mentioned above may raise tentative doubt about the usefulness of electrically evoked TMG parameters in order to detect muscle stiffness decreases after FR indicating any assumed inhibition of neuromuscular activation, as suggested earlier by Young et al. (2018) referring to their H-reflex inhibition findings. Summing up the literature, it can be suggested that TMG contractile properties may represent muscle stiffness increases after fatiguing exercise protocols (Macgregor et al., 2016), but any suspected implications for stiffness decreases representing muscle relaxation given as increased Dm values after FR remain questionable (Macgregor et al., 2018b). Thus, the inconsistent findings in terms of mechanomyography after FR stiffness alterations might be due to the passive (MMT) or active (TMG) character of the assessment devices. With respect to the passive character, the shear wave elastography is deemed to be more similar to MMT.

Taken together, in accordance with Phillips et al. (2021), we assume that longer FR applications are more adequate for maximizing local microcirculation. This could be of value during warm-up and could explain FR benefits in terms of an increased flexibility (Beardsley and Skarabot, 2015). At higher tissue temperature and perfusion, viscosity seems to decrease (Schleip, 2003), which fits with the finding of reduced post-FR tissue stiffness in the present study.

As a novelty and apart from one study investigating manually applied massage techniques (Perez-Bellmunt et al., 2021), this study investigated FR effects on passive stiffness using two concurrent mechanomyographic approaches in order to differentiate between the tissues' resistive torque and the muscles' involuntary contractile properties. However, we focussed on peripheral physiological mechanisms, exclusively. This may limit our conclusions as FR pressure may affect local tissues' properties like the myofascial restriction or fluid content changes as well as global neurophysiological mechanisms through central nervous system regulations reported for deep tissue massage (Weerapong et al., 2005) and FR devices (Cheatham and Stull, 2019). Beside the potentially limiting elapsed time between FR and the assessments of probably short-lived stiffness alterations (Konrad et al., 2019), we did not monitor parasympathetic parameters like heart rate variability and our study design used the contra-lateral limb as a control function (c.f. (Perez-Bellmunt et al., 2021)), which might influence the discussion of local or global FR effects (Macgregor et al., 2018a). Moreover, our results might be limited due to our sample characteristics, since we investigated recreational athletes that were familiar with FR, but had only limited FR experience in their daily exercise routine, which might have hampered physiological responses reported earlier for FR experienced recreational athletes (Mayer et al., 2020). Despite the advantages of a randomized cross-over design and a sample size comparable to similar earlier investigations (Baumgart et al., 2019; Macgregor et al., 2018a; Wilke et al., 2019), our study might have been underpowered with a sample size of 20 participants implying assumed strong effects. However, first, we exceeded the 14 participants found to be required in the sample size calculation. Second, our post hoc power analysis revealed a power of 0.92 assuming a strong effect size for our 2-way rANOVA data model. But with respect to our pair-wise t-test comparisons for pre- and post-test differences with observed effect sizes of maximally $dz = 0.5$, a post hoc analysis showed a power of 0.57, only. In sum, we therefore assume that our sample size was sufficient, but it was not justified to assume strong effect sizes.

Conclusion

Our data suggest that alterations of the treated tissues' stiffness and the local tissues' perfusion may be assumed as underlying mechanisms of FR effects, although outcome changes did not exceed the respective statistical MDC thresholds. For practical applications, it was apparent that longer FR durations promoted pronounced increases of blood-flow, supporting ideas of a relevant dose-response dependency. Specifically, a total duration of two minutes (combined over two sets) seems to be enough for stiffness reducing warm-up purposes. Apart from additional varying combinations of dose-response conditions and cumulative effects of repeated sessions, further research is needed to

understand probable effects on parasympathetic outcomes representing systemic physiological responses to locally applied FR stimulations.

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Key points

- There is a lack of evidence regarding the dose-response conditions and the according underlying mechanisms of foam rolling for practical applications.
- A two minutes duration (combined in two sets of 60 seconds) was enough to reduce tissue stiffness of the anterior thigh in healthy active adults, while increases of tissue perfusion needed longer foam rolling duration
- The observed effects may help to constitute practical training recommendations in order to increase sport-specific warm-up purposes.

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