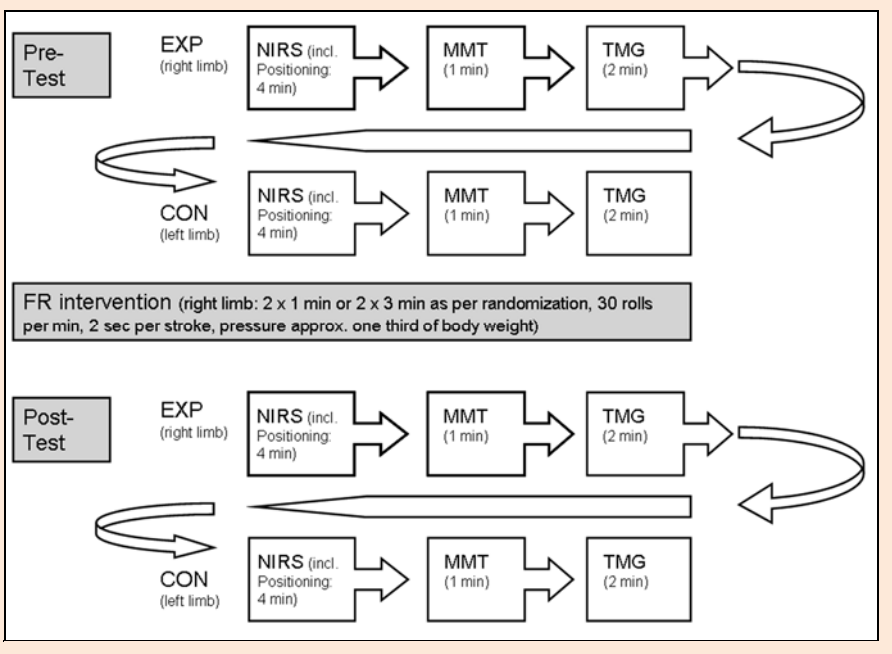

Figure 3. Data assessment schedule flow-chart.

(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 (MyotonPro®, 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 ($S = amax \times m/\Delta l$). 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 interindividually 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) η^2part	F[1, 19]	(p) η^2part	F[1, 19]	(p) η^2part
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 √2, with SEM = SD x √[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.

Acknowledgements

Jan Schroeder and Jan Wilke contributed equally. The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available, but are available from the corresponding author who was an organizer of the study.

References

Bailey, L., Samuel, D., Warner, M. and Stokes, M. (2013) Parameters representing muscle tone, elasticity and stiffness of biceps brachii in healthy older males: symmetry and within-session reliability using the MyotonPRO. *Neurological Disorders* **1**. https://doi.org/10.4172/2329-6895.1000116

Baumgart, C., Freiwald, J., Kuhnemann, M., Hotfiel, T., Huttel, M. and Hoppe, M.W. (2019) Foam Rolling of the Calf and Anterior Thigh: Biomechanical Loads and Acute Effects on Vertical Jump Height and Muscle Stiffness. *Sports (Basel)* **7,** 27. https://doi.org/10.3390/sports7010027

Beardsley, C. and Skarabot, J. (2015) Effects of self-myofascial release: A systematic review. *Journal of Bodywork and Movement Therapies* **19,** 747-758. https://doi.org/10.1016/j.jbmt.2015.08.007

Behm, D.G. and Wilke, J. (2019) Do Self-Myofascial Release Devices Release Myofascia? Rolling Mechanisms: A Narrative Review. *Sports Medicine* **49,** 1173-1181. https://doi.org/10.1007/s40279-019-01149-y

Casanova, N., Reis, J.F., Vaz, J.R., Machado, R., Mendes, B., Button, D.C., Pezarat-Correia, P. and Freitas, S.R. (2018) Effects of roller massager on muscle recovery after exercise-induced muscle damage. *Journal of Sports Sciences* **36,** 56-63. https://doi.org/10.1080/02640414.2017.1280609

Cheatham, S.W. and Stull, K.R. (2019) Roller massage: Comparison of three different surface type pattern foam rollers on passive knee range of motion and pain perception. *Journal of Bodywork and Movement Therapies* **23,** 555-560. https://doi.org/10.1016/j.jbmt.2019.05.002

Dębski, P., Białas, E. and Gnat, R. (2019) The Parameters of Foam Rolling, Self-Myofascial Release Treatment: A Review of the Literature. *Biomedical Human Kinetics* **11,** 36-46. https://doi.org/10.2478/bhk-2019-0005

Ditroilo, M., Hunter, A.M., Haslam, S. and De Vito, G. (2011) The effectiveness of two novel techniques in establishing the mechanical and contractile responses of biceps femoris. *Physiological Measurement* **32,** 1315-1326. https://doi.org/10.1088/0967-3334/32/8/020

García-García, O. (2015) Preseason Neuromuscular Profile of Knee Extensor and Flexor Muscles in Elite Amateur Road Cyclist's Assessment through Tensiomyography. *Annals of Sports Medicine and Research* **2,** 1024.

Grabow, L., Young, J., Alcock, L., Quigley, P., Byrne, J., Granacher, U., Škarabot, J. and Behm, D. (2018) Higher Quadriceps Roller Massage Forces Do Not Amplify Range-of-Motion Increases nor Impair Strength and Jump Performance. *The Journal of Strength & Conditioning Research* **32,** 3059-3069. https://doi.org/10.1519/JSC.0000000000001906

Hendricks, S., Hill, H., Hollander, S.D., Lombard, W. and Parker, R. (2020) Effects of foam rolling on performance and recovery: A systematic review of the literature to guide practitioners on the use of foam rolling. *Journal of Bodywork and Movement Therapies* **24,** 151-174. https://doi.org/10.1016/j.jbmt.2019.10.019

Hotfiel, T., Swoboda, B., Krinner, S., Grim, C., Engelhardt, M., Uder, M. and Heiss, R.U. (2017) Acute Effects of Lateral Thigh Foam Rolling on Arterial Tissue Perfusion Determined by Spectral Doppler and Power Doppler Ultrasound. *The Journal of Strength & Conditioning Research* **31,** 893-900. https://doi.org/10.1519/JSC.0000000000001641

Kell, R.T., Farag, M. and Bhambhani, Y. (2004) Reliability of erector spinae oxygenation and blood volume responses using near-infrared spectroscopy in healthy males. *European Journal of Applied Physiology* **91,** 499-507. https://doi.org/10.1007/s00421-003-1014-0

Konrad, A., Reiner, M.M., Thaller, S. and Tilp, M. (2019) The time course of muscle-tendon properties and function responses of a five-minute static stretching exercise. *European Journal of Sport Science* **19,** 1195-1203. https://doi.org/10.1080/17461391.2019.1580319

Macgregor, L.J., Ditroilo, M., Smith, I.J., Fairweather, M.M. and Hunter, A.M. (2016) Reduced Radial Displacement of the Gastrocnemius Medialis Muscle After Electrically Elicited Fatigue. *Journal of Sport Rehabilitation* **25,** 241-247. https://doi.org/10.1123/jsr.2014-0325

Macgregor, L.J., Fairweather, M.M., Bennett, R.M. and Hunter, A.M. (2018a) The Effect of Foam Rolling for Three Consecutive Days on Muscular Efficiency and Range of Motion. *Sports Medicine - Open* **4,** 26. https://doi.org/10.1186/s40798-018-0141-4

Macgregor, L.J., Hunter, A.M., Orizio, C., Fairweather, M.M. and Ditroilo, M. (2018b) Assessment of Skeletal Muscle Contractile Properties by Radial Displacement: The Case for Tensiomyography. *Sports Medicine* **48,** 1607-1620. https://doi.org/10.1007/s40279-018-0912-6

Martínez-Cabrera, F.I. and Núñez-Sánchez, F.J. (2016) Acute Effect of a Foam Roller on the Mechanical Properties of the Rectus Femoris Based on Tensiomyography in Soccer Players. *International Journal of Human Movement and Sports Sciences* **4,** 26-32. https://doi.org/10.13189/saj.2016.040203

Mayer, I., Hoppe, M.W., Freiwald, J., Heiss, R., Engelhardt, M., Grim, C., Lutter, C., Huettel, M., Forst, R. and Hotfiel, T. (2020) Different Effects of Foam Rolling on Passive Tissue Stiffness in Experienced and Nonexperienced Athletes. *Journal of Sport Rehabilitation* **29,** 926-933. https://doi.org/10.1123/jsr.2019-0172

Monteiro Rodrigues, L., Rocha, C., Ferreira, H.T. and Silva, H.N. (2020) Lower limb massage in humans increases local perfusion and impacts systemic hemodynamics. *Journal of Applied Physiology* **128,** 1217-1226. https://doi.org/10.1152/japplphysiol.00437.2019

Morales-Artacho, A.J., Lacourpaille, L. and Guilhem, G. (2017) Effects of warm-up on hamstring muscles stiffness: Cycling vs foam rolling. *Scandinavian Journal of Medicine & Science in Sports* **27,** 1959-1969. https://doi.org/10.1111/sms.12832

Mullix, J., Warner, M. and Stokes, M. (2012) Testing muscle tone and mechanical properties of rectus femoris and biceps femoris using a novel hand held MyotonPRO device: relative ratios and reliability. *Working Papers in Health Sciences* **1,** 1-8.

Murray, A., Jones , T., Horobeanu, C., Turner, A. and Sproule, J. (2016) Sixty seconds of foam rolling does not affect functional flexibility or change muscle temperature in adolescent athletes. *International Journal of Sports Physical Therapy* **11,** 765-776.

Nakamura, M., Onuma, R., Kiyono, R., Yasaka, K., Sato, S., Yahata, K., Fukaya, T. and Konrad, A. (2021) The Acute and Prolonged Effects of Different Durations of Foam Rolling on Range of Motion, Muscle Stiffness, and Muscle Strength. *Journal of Sports Science and Medicine* **20,** 62-68. https://doi.org/10.52082/jssm.2021.62

Okamoto, T., Masuhara, M. and Ikuta, K. (2013) Acute Effects of Self-Myofascial Release using a Foam Roller on Arterial Function. *The Journal of Strength & Conditioning Research* **28,** 69-73. https://doi.org/10.1519/JSC.0b013e31829480f5

Owen-Reece, H., Smith, M., Elwell, C.E. and Goldstone, J.C. (1999) Near infrared spectroscopy. *British Journal of Anaesthesia* **82,** 418-426. https://doi.org/10.1093/bja/82.3.418

Perez-Bellmunt, A., Labata-Lezaun, N., Llurda-Almuzara, L., Rodriguez-Sanz, J., Gonzalez-Rueda, V., Bueno-Gracia, E., Celik, D. and Lopez-de-Celis, C. (2021) Effects of a Massage Protocol in Tensiomyographic and Myotonometric Proprieties. *International Journal of Environmental Research and Public Health* **18**. https://doi.org/10.3390/ijerph18083891

Phillips, J., Diggin, D., King, D.L. and Sforzo, G.A. (2021) Effect of Varying Self-myofascial Release Duration on Subsequent Athletic Performance. *The Journal of Strength & Conditioning Research* **35,** 746-753.

https://doi.org/10.1519/JSC.0000000000002751
Pruyn, E.C., Watsford, M.L. and Murphy, A.J. (2016) Validity and reliability of three methods of stiffness assessment. *Journal of Sport and Health Science* **5,** 476-483. https://doi.org/10.1016/j.jshs.2015.12.001
Reiner, M.M., Glashuttner, C., Bernsteiner, D., Tilp, M., Guilhem, G., Morales-Artacho, A. and Konrad, A. (2021) A comparison of foam rolling and vibration foam rolling on the quadriceps muscle function and mechanical properties. *European Journal of Applied Physiology* **121,** 1461-1471. https://doi.org/10.1007/s00421-021-04619-2
Schleip, R. (2003) Fascial plasticity – a new neurobiological explanation: Part 1. *Journal of Bodywork and Movement Therapies* **7,** 11-19. https://doi.org/10.1016/S1360-8592(02)00067-0
Schroeder, J., Lueders, L., Schmidt, M., Braumann, K.-M. and Hollander, K. (2019) Foam rolling effects on soft tissue tone, elasticity and stiffness in the time course of recovery after weight training. *Sports Orthopaedics and Traumatology* **35,** 171-177. https://doi.org/10.1016/j.orthtr.2018.11.003
Schroeder, J., Renk, V., Braumann, K.-M. and Hollander, K. (2017) Acute Foam Rolling effects on contractile properties of the m. biceps femoris. *German Journal of Exercise and Sport Research* **47,** 294-300. https://doi.org/10.1007/s12662-017-0467-y
Skinner, B., Moss, R. and Hammond, L. (2020) A systematic review and meta-analysis of the effects of foam rolling on range of motion, recovery and markers of athletic performance. *Journal of Bodywork and Movement Therapies* **24,** 105-122. https://doi.org/10.1016/j.jbmt.2020.01.007
Sullivan, K., Silvey, D., Button, D. and Behm, D. (2013) Roller-massager application to the hamstrings increases sit-and-reach range of motion within five to ten seconds without performance impairments. *International Journal of Sports Physical Therapy* **8,** 228-236.
Tous-Fajardo, J., Moras, G., Rodriguez-Jimenez, S., Usach, R., Doutres, D.M. and Maffiuletti, N.A. (2010) Inter-rater reliability of muscle contractile property measurements using non-invasive tensiomyography. *Journal of Electromyography and Kinesiology* **20,** 761-766. https://doi.org/10.1016/j.jelekin.2010.02.008
Weerapong, P., Hume, P.A. and Kolt, G.S. (2005) The mechanisms of massage and effects on performance, muscle recovery and injury prevention. *Sports Medicine* **35,** 235-256. https://doi.org/10.2165/00007256-200535030-00004
Weir, J.P. (2005) Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *The Journal of Strength & Conditioning Research* **19,** 231-240. https://doi.org/10.1519/15184.1
Wiewelhove, T., Doweling, A., Schneider, C., Hottenrott, L., Meyer, T., Kellmann, M., Pfeiffer, M. and Ferrauti, A. (2019) A Meta-Analysis of the Effects of Foam Rolling on Performance and Recovery. *Frontiers Physiology* **10,** 376. https://doi.org/10.3389/fphys.2019.00376
Wilke, J., Muller, A.L., Giesche, F., Power, G., Ahmedi, H. and Behm, D.G. (2020) Acute Effects of Foam Rolling on Range of Motion in Healthy Adults: A Systematic Review with Multilevel Meta-analysis. *Sports Medicine* **50,** 387-402. https://doi.org/10.1007/s40279-019-01205-7
Wilke, J., Niemeyer, P., Niederer, D., Schleip, R. and Banzer, W. (2019) Influence of Foam Rolling Velocity on Knee Range of Motion and Tissue Stiffness: A Randomized, Controlled Crossover Trial. *Journal of Sport Rehabilitation* **28,** 711-715. https://doi.org/10.1123/jsr.2018-0041
Wilson, H., Johnson, M. and Francis, P. (2018) Repeated stimulation, inter-stimulus interval and inter-electrode distance alters muscle contractile properties as measured by Tensiomyography. *PloS One* **13**. https://doi.org/10.1371/journal.pone.0191965
Young, J.D., Spence, A.J. and Behm, D.G. (2018) Roller massage decreases spinal excitability to the soleus. *Journal of Applied Physiology* **124,** 950-959. https://doi.org/10.1152/japplphysiol.00732.2017

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.

AUTHOR BIOGRAPHY

Jan SCHROEDER
Employment
University of Hamburg, Faculty of Psychology and Human Movement Science, Department of Sports and Exercise Medicine, Hamburg, Germany
Degree
Ph.D.
Research interests
Preventive and rehabilitative sports medicine
E-mail: jan.schroeder@uni-hamburg.de

Jan WILKE
Employment
Goethe University Frankfurt, Department of Sports Medicine, Frankfurt am Main, Germany
Degree
Ph.D.
Research interests
Preventive and rehabilitative sports medicine, strength and mobility exercise, perceptual-cognitive function
E-mail: wilke@sport.uni-frankfurt.de

Karsten HOLLANDER
Employment
MSH Medical School Hamburg, Institute of Interdisciplinary Exercise Science and Sports Medicine, Hamburg, Germany
Degree
M.D., Ph.D.
Research interests
Sports medicine, biomechanics, injury epidemiology and prevention, running.
E-mail: karsten.hollander@medicalschool-hamburg.de

✉ **Jan Wilke (Ph.D.)**
Goethe University Frankfurt, Institute of Occupational, Social and Environmental Medicine, Theodor-Stern-Kai 7, D-60590 Frankfurt am Main, Germany