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Acute effects of foam rolling on passive stiffness, stretch sensation and fascial sliding: A randomized controlled trial

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ABSTRACT

Purpose: Foam Rolling (FR), aims to mimic the effects of manual therapy and tackle dysfunctions of the skeletal muscle and connective tissue. It has been shown to induce improvements in flexibility, but the underlying mechanisms are poorly understood. The aim of the present study was to further elucidate the acute, systemic and tissue-specific responses evoked by FR.

Methods: In a crossover study, 16 (34 ± 6y, 6f) participants received all of the following interventions in a random order: a) 2 × 60 seconds of FR at the anterior thigh, b) 2 × 60 seconds of passive static stretching of the anterior thigh (SS), and c) no intervention (CON). Maximal active and passive knee flexion range of motion (ROM), passive stiffness, sliding of fascial layers, as well as knee flexion angle of first subjectively perceived stretch sensation (FSS) were evaluated before and directly after each intervention.

Results: Flexibility increased only after, FR (active (+1.8 ± 1.9%) and passive ROM (+3.4 ± 2.7%), p = .006, respectively) and SS (passive ROM (+3.2 ± 3.5%), p = .002). Angle of FSS was altered following FR (+4.3° (95% CI: 1.4°–7.2°)) and SS (+6.7° (3.7°–9.6°)), while tissue stiffness remained unchanged after any intervention compared to baseline. Movement of the deepest layer (−5.7 mm (−11.3 mm to −0.1 mm)) as well as intrafascial sliding between deep and superficial layer (−4.9 mm (−9.mm to −0.7 mm)) decreased only after FR.

Conclusion: FR improved knee flexion ROM without altering passive stiffness, but modified the perception of stretch as well as the mobility of the deep layer of the fascia lata. The mechanisms leading to altered fascial sliding merit further investigation.

1. Introduction

Foam rolling (FR) is an intensive self-treatment with rigid polypropylene rollers aiming to tackle dysfunctions of the skeletal muscle and connective tissue. It claims to mimic the effects of manual therapy techniques using compressive force to muscle and soft tissue (MacDonald et al., 2013). Recent studies indicate that FR (among other effects) improves range of motion (ROM), while the effect on neuromuscular performance remains unclear (Beardsley & Škarabot, 2015; Cheatham, Kolber, Cain, & Lee, 2015; Monteiro et al., 2019; Schroeder & Best, 2015).

Enhanced ROM following FR might be attributed to cortical reactions, i.e., increased stretch tolerance and modified stretch sensation. Both neurophysiological phenomena have been shown to occur after static stretching (Cabido et al., 2014; Halbertsma, van Bolhuis, & Goeken, 1996; Magnusson, Simonsen, Aagaard, Sørensen, & Kjaer, 1996) and may be similarly relevant after FR

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(Bradbury-Squires et al., 2015; Halperin, Aboodarda, Button, Andersen, & Behm, 2014). Another line of evidence assumes that morphological adaptations represent possible underlying cause. An often hypothesized tissue-specific effect of FR is found in the alteration of passive tissue stiffness, as occurring after static stretching (Magnusson et al., 1995; McNair, Dombroski, Hewson, & Stanley, 2001; Nordez, Cornu, & McNair, 2006; Ryan et al., 2008; Whatman, Knappstein, & Hume, 2006). A plethora of studies have demonstrated the existence of myofibroblasts (and their participation in stiffness regulation) in fascia (Schleip, Klingler, & Lehmann-Horn, 2005; Staubesand & Li, 1996). Moreover, fascial hydration has been shown to alter biomechanical tissue properties in vitro (Schleip et al., 2012). Compression of the muscle and the surrounding fascial tissue (as occurring during FR) might hence stimulate contractile cell activity, affect tissue hydration (Beardsley & Škarabot, 2015; Schleip & Müller, 2013) as well as viscoelastic tissue properties (Barnes, 1997).

Beyond stiffness changes, another physiological explanation for the increase in ROM after FR are gliding property alterations of the connective tissues. The fasciae surrounding the muscles of the lower extremity are composed of multiple fibrous layers. Loose connective tissue enriched with hyaluronic acid (Stecco et al., 2008, 2011) allows these layers to slide against each other during motion (e.g. contraction or elongation of the underlying muscle) (Stecco et al., 2008). Several authors assume a positive effect of FR on fascial sliding properties, e.g. through breaking up adhesions, loosening of cross-links and altering the viscoelastic and thixotropic properties of the fascia (Barnes, 1997; Beardsley & Škarabot, 2015; Schleip & Müller, 2013). One recent study showed an acute increased overall mobility of the thoracolumbar fascia after FR application to the surrounding tissue (Griefahn, Oehlmann, Zalpour, & von Piekartz, 2017), but the direct effect of FR on fascial tissues remains unclear (Behm & Wilke, 2019).

Although the different presented mechanisms seem plausible, there is little to no scientific evidence for or against most of them. Most available studies on FR solely focused on functional parameters (e.g. flexibility, strength, recovery) in practice-based settings. However, knowledge of the underlying physiological processes would allow for a more effective selection of therapeutic and performance-related indications. The aim of the present study therefore was to evaluate the acute effects of FR on ROM, passive tissue stiffness and stretch sensation of the anterior thigh muscles as well as the sliding properties of the associated fasciae.

2. Methods

2.1. Study design

The methodological approach of the study has been described thoroughly before (Krause, Wilke, Niederer, Vogt, & Banzer, 2017). Briefly, the study adopted a randomized crossover design and was approved by the local Ethics Committee of the Faculty of Psychology and Sport Science (Goethe-University Frankfurt, number 2016–38). After signing informed consent, healthy participants received all of the following interventions in a random order:

a) single set of 2 × 60 seconds of FR at the anterior thigh (FR),
b) single set of 2 × 60 seconds passive static stretching of the anterior thigh (SS) and
c) no intervention (CON).

Balanced permutation randomization sequences of treatment orders as well as body side were generated using an electronic randomization algorithm (www.randomization.com). At least two days prior to the experimental conditions, volunteers participated in a standardized familiarization session including all measurements and interventions in order to minimize learning effects. Before each condition, main outcomes were measured. Immediately (< 30 s) after the intervention or control session, post-intervention outcome parameters were collected (see Fig. 1). All experimental trials were performed at the same time of the day (± 2 h), with a wash-out phase of at least three days between each of the three experimental testing sessions (Ryan et al., 2008).

2.2. Sample

Based on previous studies on the effect of static stretching on tissue stiffness (Whatman et al., 2006), we expected a medium effect size ($f^2 = 0.25$; $\alpha = 0.05$ and $\beta = 0.80$). An *a-priori* sample size calculation for the three-armed crossover trial (assumed dropout of 10%) using G*Power (G*Power, version 3.1, Heinrich-Heine-University Düsseldorf, Germany), determined a sample size of n = 48 datasets (3 conditions × 16 participants). Hence, 16 participants were included into the study (see Table 1). Inclusion criteria consisted of (1) age between 18 and 40 years and (2) no history of orthopedic injuries or surgery in the lower extremity in the last twelve months. Exclusion criteria were any history of psychiatric, cardiovascular, endocrine, neurological, or metabolic disorders, any current medication that might affect pain perception or proprioception, acute muscle soreness, pregnancy or nursing period and any current nonspecific musculoskeletal disorders.

2.3. Interventions

2.3.1. FR intervention

Both interventions consisted of two 60-second sets of dynamic FR with a foam roller respectively static stretching of the anterior thigh respectively the m. quadriceps femoris. The FR intervention was performed in prone position lying on a polypropulene foam roller (length: 30 cm, diameter: 15 cm, Blackroll, Bottighofen, Switzerland). Applying pressure to the tissue of the anterior thigh, participants performed a rolling motion from the proximal aspect of the thigh (inferior to the anterior superior iliac spine) to the

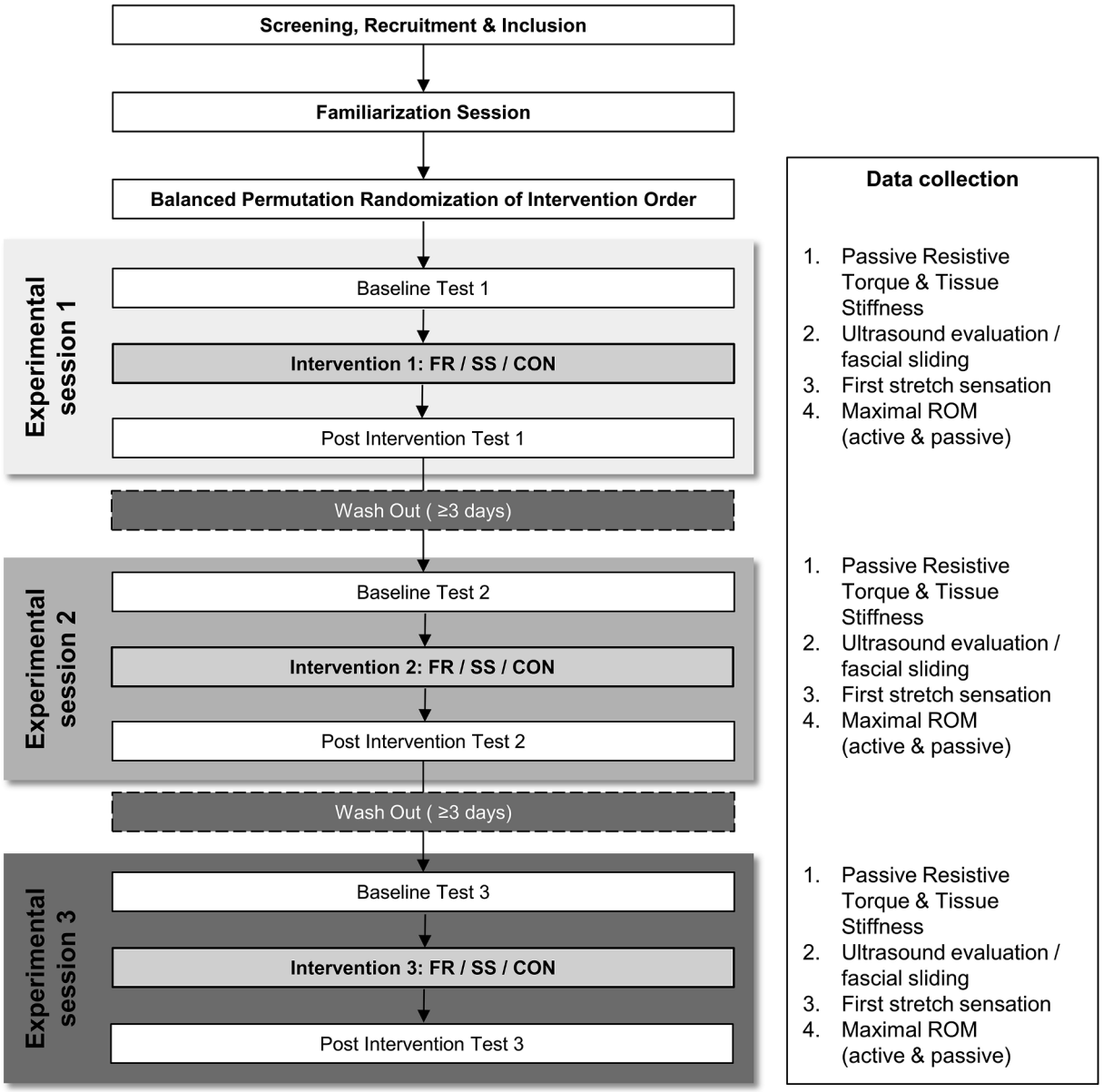

Fig. 1. Study flow chart: FR = foam rolling, SS = static stretching, CON = passive control, ROM = Range of Motion.

Table 1
Characteristics of study sample.

	n	Age [y]	Height [cm]	Weight [kg]	BMI [kg/m^2]
Female	6	33.5 ± 5.6	168.5 ± 6.6	58.2 ± 4.8	20.5 ± 1.9
Male	10	31.2 ± 4.8	183.0 ± 6.2	90.2 ± 17.0	27.1 ± 5.9
Total	16	32.1 ± 5.0	177.6 ± 9.5	78.2 ± 20.9	24.6 ± 5.8

Legend: n = number; BMI = body mass index.

knee. Once the foam roller reached the superior border of the patella, participants were instructed to return to the starting position and continue the sequence for the remainder of the 60 s. Rolling frequency was standardized using a metronome set (15 complete rolling cycles in 60 s equaling 0.25 Hz). Pressure was subjectively controlled with a target Numerical Rating Scale (NRS) rating of 7/10 (0 representing no discomfort and 10 representing maximal discomfort) during the intervention. After a 30 s-break in relaxed prone position, participants performed the second bout.

2.3.2. Static stretching

Also passive static stretching of the anterior thigh muscles was performed in prone position with a pre-stretch of the hip (200° in total) using a bed wedge with a 20° inclination (Krause et al., 2017). The same investigator performed all stretching interventions. Stretch intensity was adjusted according to the feedback of the participant (target NRS rating of 7/10) and then held at a constant angle for 60 s. After a 30-second rest period in a relaxed position and a second bout of stretching was performed at the same target intensity for 60 s.

2.4. Outcomes

2.4.1. Range of motion

Maximal active and passive knee flexion ROM in the sagittal plane were assessed in prone position (as described above). A 3D-ultrasonographic movement analysis system (Zebris CMS20, Zebris Medical GmbH, Isny, Germany) was used. Objectivity as well as intrarater reliability have been described as good to excellent (r = 0.84–0.96) (Natalis & Konig, 1999). A triplet of active ultrasonographic markers was positioned at the lateral aspect of the lower leg, a second reference triplet was placed on the lateral thigh. Participants performed three consecutive, maximal active knee flexion-extension movements at self-selected velocity followed by three maximal passive knee flexion-extension cycles performed by the investigator. In the latter condition, ROM was adjusted according to the participants feedback. Data were recorded in three dimensions at a 20 Hz sampling rate. Maximal active as well as passive knee flexion ROM in was calculated as the maximal displacement of the lower leg relative to the starting position.

2.4.2. Passive resistive torque & tissue stiffness

Passive resistive torque (PRT) as the resistance against passive movement of the quadriceps muscle-tendon-unit was evaluated using a computerized isokinetic dynamometer (Biodex system 3 Pro, Biodex Medical, Shirley, NY, USA) in an identical measurement setup for pre and post assessments. Participants were placed in a standardized position on the seat of the dynamometer (see Fig. 2). The pelvis as well as the thigh of the tested leg were fixed with restriction straps to minimize secondary movement. The opposite hip was fixed at 90° flexion to limit pelvic and lumbar motion. The knee axis was aligned with the rotational axis of the dynamometer. To obtain PRT, the lower leg was moved from full knee extension (0°) to maximal achievable knee flexion angle with an angular velocity of 5°/s in passive mode of the dynamometer. Torque (T) and angle (θ) were recorded at 100 Hz. This procedure has been described as a reliable method to evaluate passive tissue properties for various positions and muscles (ICC ranging from 0.88 to 1.00) (Araujo et al., 2011; Bressel, Larsen, McNair, & Cronin, 2004; Carvalhais et al., 2011; Gajdosik, Vander Linden, & Williams, 1999; Nordez, Casari, & Cornu, 2008; Porter, Andersson, Hellstrom, & Miller, 2002). Torque data were gravity-corrected and filtered using a Butterworth zero-lag fourth-order low-pass filter with a 10 Hz cut-off frequency (Ryan et al., 2008). Mean torque data from the final three passive knee flexion cycles was used for further analysis. A fourth order polynomial model was fitted on the T-θ data, and stiffness was calculated using the slope of the model (Nordez, McNair, Casari, & Cornu, 2008, 2010). Passive torque as well as stiffness from four angles during the last 13° of passive tissue tensioning (13°, 9°, 5° and 1° before the end of the movement) as well as

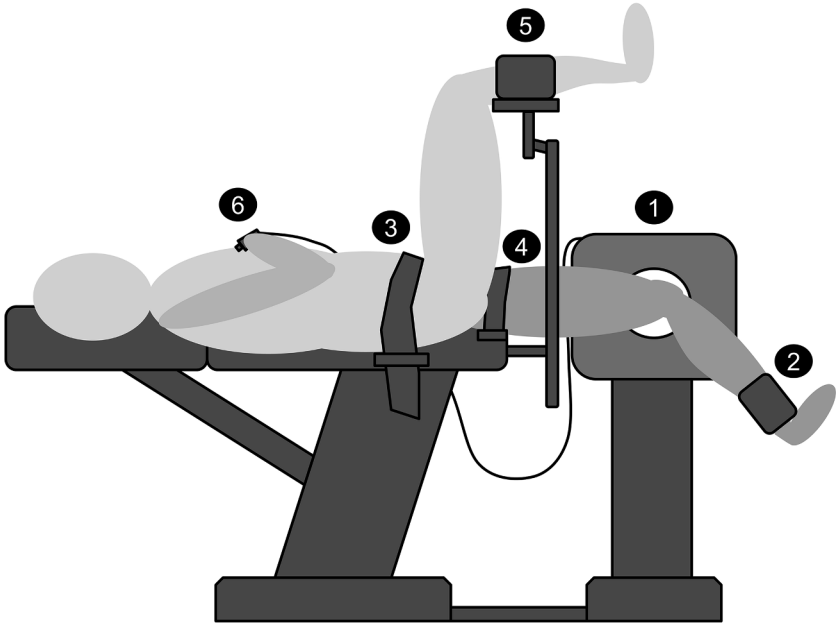

Fig. 2. Schematic illustration of positioning of participants on the isokinetic dynamometer: 1: Isokinetic Dynamometer, 2: Fixation of the lower leg of the tested limb, 3: Pelvic stabilization strap, 4: Thigh stabilization strap, 5: Fixation device for the untested limb (height adjusted to fixate the hip at 90° flexion), 6: Stop-Switch for evaluation of stretch sensation.

mean torque and stiffness from those angles were calculated (Ryan et al., 2008). To monitor myoelectric activity, surface electromyography was used with two surface electrodes (Ambu Blue Sensor, Ambu GmbH, Bad Nauheim, Germany) placed on the head of the M. rectus femoris with an 8 mm inter-electrode distance and one reference electrode on the patella, according to international recommendations (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Participants were provided with live biofeedback of muscle activity to prevent involuntary muscle contraction.

2.4.3. Stretch sensation

The position of the first self-perceived stretch sensation (FSS) was quantified using the isokinetic dynamometer in the above-described position. In passive mode, the knee was flexed from full extension to flexion at 5°/s. Participants used a switch to stop the passive movement at the position of first stretch sensation. Mean angle from three consecutive passive movements was quantified as angle of first stretch sensation.

2.4.4. Fascial sliding

While assessing PRT, the probe of a high-resolution ultrasound (US) device (Siemens Acuson X300, Siemens Healthcare GmbH, Erlangen, Germany) was positioned on the thigh. Sliding of fascial layers was quantified with a frame-by-frame cross correlation algorithm of the generated ultrasound images obtained during the passive movement. The cross-correlation method developed in MATLAB (The Math-Works, Inc, Natick, MA) by Dilley and colleagues (Dilley, Greening, Lynn, Leary, & Morris, 2001) was used to calculate the correlation coefficient between the pixel grey levels for selected rectangle-shaped regions of interest (ROI) in two adjacent images. The pixel shift providing the maximum correlation coefficient corresponds to the relative movement between two frames (Dilley et al., 2001). The method has been extensively used to quantify nerve movement and represents a reliable method to quantify tissue movement in vivo (ICC ranging from 0.70 to 0.99) (Boyd, Gray, Dilley, Wanek, & Topp, 2012; Carroll, Yau, Rome, & Hing, 2012; Dilley et al., 2001; Dilley, Summerhayes, & Lynn, 2007; Ellis, Hing, & McNair, 2012; Ellis, Hing, Dilley, & McNair, 2008).

The linear array US-transducer (4–11.4 MHz, 38.4 mm footprint) was placed on the proximal third of the muscle belly of the M. rectus femoris and sequences of 20 s were captured at 10 Hz during passive knee flexion (starting at 0° until 100° of knee flexion at 5°/s). Ultrasonic-transducer location was marked on the skin with a permanent marker. Participants were instructed to renew the marker on a daily basis to ensure equal transducer placement at all three testing sessions. Six ROIs were selected on the superficial and deep layer of the fascia lata, respectively, to quantify sliding of these layers during passive stretching of the underlying muscle (see Fig. 3). For the final analysis, videos with obvious artifacts due to movement of the US transducer during recording were excluded from analysis. We did not consider the first and the last five seconds of eligible videos to remove artifacts occurring due to the change of movement direction (e.g. from extension to flexion). Mean pixel shift of the six individual ROIs per fascial layer was calculated for each consecutive frame. Maximal horizontal movement of the superficial and the deep layer of the anterior fascial lata above the m. rectus femoris was calculated in millimeters (mm) and served as a quantification of fascial movement, the difference between maximal displacement of the deep and the superficial layer was calculated to quantify intrafascial sliding.

2.5. Statistical analysis

Statistical calculations were performed after checking the underlying assumptions for parametric or non-parametric testing. Friedman-test followed by post-hoc Wilcoxon signed-rank test including Bonferroni-Holm-Correction were calculated for changes in flexibility. Absolute pre to post differences in passive torque and stiffness were checked for significance using five (one for each angle and one for mean values across all angles) 1 × 3 ANCOVAs (angle × intervention) controlling for baseline toque/stiffness. In case of statistically significant effects for baseline co-variate or intervention, estimated marginal means with 95% confidence-intervals (CI) were used to check for statistically significant intervention effects and group differences. The same procedure was applied for the angle of FSS as well as parameters of fascial sliding. Effect sizes were calculated using absolute pre/post differences and standard deviations of baseline values (Sullivan & Feinn, 2012). Intraday reliability for measures of fascial sliding were calculated by means of Intraclass Correlation Coefficients ($ICC_{2,1}$, CON only). The software “SPSS” (version 22.0, SPSS Inc., Chicago, Illinois) was used for all statistical analyses.

3. Results

3.1. Range of motion

Friedman-test revealed a statistically significant omnibus effect for active ($Chi^2 = 16.2$, $p = .007$) as well as passive ROM ($Chi^2 = 16.1$, $p = .007$). Post-hoc Wilcoxon tests indicated an increased active ROM after FR, while no statistically significant changes were observed after static stretching or passive control. Further, post-hoc Wilcoxon test indicated a statistically significant increase in passive ROM after FR and stretching, while it remained unchanged after passive control (Table 2).

3.2. Passive resistive torque & passive stiffness

Torque and stiffness increased physiologically with increasing knee flexion angle. Individual ANCOVAS showed no effect of treatment for either passive torque or stiffness in any angle ($p > .05$, see Fig. 4A).

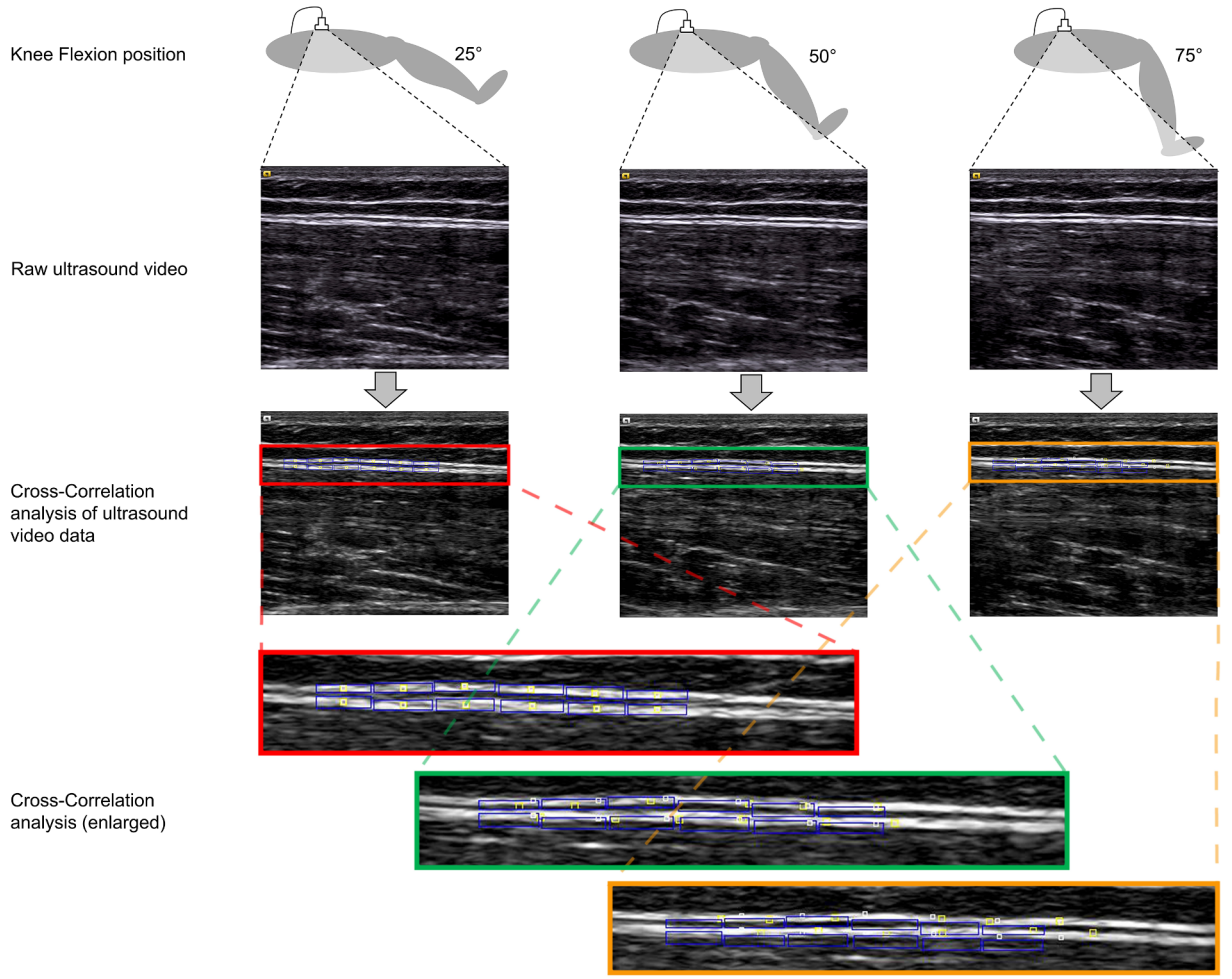

Fig. 3. Exemplary visualization of US-evaluation and Cross-Correlation Analysis for quantification of fascial movement: Blue boxes: individual ROIs, white rectangles: mean movement of all ROIs, yellow rectangles: movement of individual ROIs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Results for active and passive ROM measurements pre and post Intervention.

		Pre median (range) [°]	Post median (range) [°]	mean change [%] ± SD	p-value	ES
FR	active ROM	135.2 (115.8–146.2)	137.1 (118.2–146.8)	1.8 ± 1.9	0.006	0.25
	passive ROM	143.4 (119.9–158.4)	150.3 (131.1–161.7)	3.4 ± 2.7	0.006	0.47
SS	active ROM	135.0 (115.2–148.7)	139.5 (118.2–145.8)	1.9 ± 3.2	0.092	0.28
	passive ROM [°]	150.5 (124.8–163.6)	156.2 (133.2–168.9)	3.2 ± 3.5	0.002	0.51
CON	active ROM	134.2 (115.2–144.7)	134.9 (110.6–146.2)	0.3 ± 3.5	0.469	0.02
	passive ROM	151.0 (124.6–163.4)	150.9 (119.9–163.8)	0.3 ± 4.2	0.861	0.02

Legend: SD = standard deviation, FR = foam rolling, SS = static stretching, CON = passive control, ES = effect size.

3.3. Stretch sensation

The ANCOVA indicated a statistically significant effect of intervention group on change of angle of FSS ($F_{(2,\ 39)} = 5.052$, $p = .011$) while controlling for baseline values. Estimated marginal means with 95%-CI showed that angle of FSS increased statistically significantly after FR (+4.3° (1.4°–7.2°) ES: 0.23) and stretching (+6.7° (3.7°–9.6°), ES: 0.55), while it remained constant after passive control (+0.3° (−2.5° to 3.1°), ES: 0.01). Additionally, the results indicate a systematic difference in angle of first stretch sensation between FR as well as stretching, respectively, and passive control (see Fig. 4B).

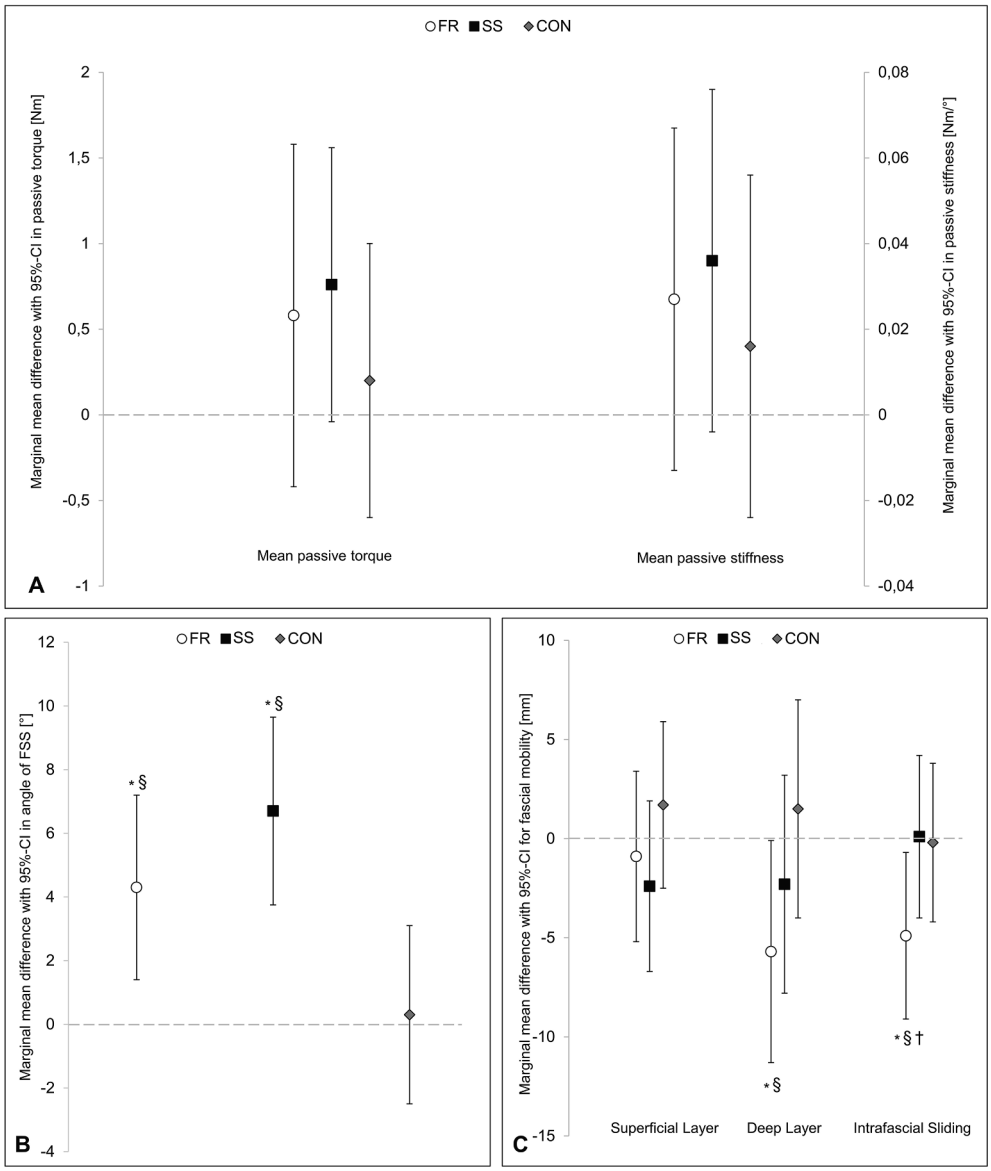

Fig. 4. Marginal mean pre to post differences with 95%-CI for measures of mean passive torque and stiffness (A), angle of first stretch sensation (B) and fascial sliding (C): FR = foam rolling, SS = static stretching, CON = passive control, * = statistically significant difference to pre-intervention, § = statistically significant difference to passive control, † = statistically significant difference to static stretching.

3.4. Fascial sliding

Baseline fascial sliding (mean ± standard error of the mean (SEM)) in the three sessions was 32.6 ± 4.0 mm for the superficial layer, 61.8 ± 5.1 mm for the deep layer and 29.2 ± 2.2 mm between both layers. Intraday reliability (ICC $_{2,1}$) of the measurement setup ranged from 0.78 to 0.96.

Neither treatment had any influence on movement of the superficial layer of the fascia lata. However, movement of the deep layer decreased statistically significantly from baseline following FR (estimated marginal means: −5.7 mm (95%-CI: −11.3 mm to −0.1 mm), ES: 0.09) while no changes were observed after SS (−2.3 mm (−7.7 mm to 3.2 mm), ES: 0.07) or CON (+1.5 mm (−4.0 mm to 6.9 mm), ES: 0.04). Results also indicate a statistically significant difference between FR and CON. Similarly, intrafascial sliding decreased statistically significantly only after FR (−4.9 mm (−9.1 mm to −0.7 mm), ES: 0.36; (SS: +0.1 mm (−3.9 mm to 4.2 mm), ES: 0; CON: −0.2 mm (−4.2 mm to 3.8 mm), ES: 0.01). The results also indicate a statistically significant difference between FR and both stretching and control, respectively (Fig. 4C).

4. Discussion

The results of the current study show that changes in active as well as passive ROM after FR do not seem to be driven by changes in passive resistance or stiffness, but rather by changes in fascial gliding of the deep layer of the fascia lata and in the perception of stretch sensation. After stretching, only the latter was altered. Thus, this is the first study to show that FR does have an impact on movement properties of independent fascial layers of the lower extremity and stretch sensation whilst SS only affects stretch sensation.

4.1. Range of motion

Our results are in accordance with recent evidence indicating a positive influence of FR on flexibility (Beardsley & Škarabot, 2015; Cheatham et al., 2015; Monteiro et al., 2019; Wiewelhove et al., 2019). After FR application at the anterior thigh, also Bradbury-Squires et al. (2015) and MacDonald et al. (2013) found an increase in passive flexibility of the knee in a kneeling lunge position. The magnitude of the effect (3.4% increase) in our sample was rather small compared to these two studies (mean change between 10 and 13%), but this might be due to differences in the measurement setup. In contrast to these findings, other authors describe no effect on flexibility after FR application at the anterior thigh (Bushell, Dawson, & Webster, 2015; Murray, Jones, Horobeanu, Turner, & Sproule, 2016; Vigotsky et al., 2015). In the latter studies, flexibility was not measured in a passive end ROM, but either as active hip extension and knee flexion (Bushell et al., 2015; Vigotsky et al., 2015) or by application of a constant stretching force (Murray et al., 2016), which hampers comparability of these results.

4.2. Passive resistive torque & passive stiffness

Neither FR nor SS had an influence on passive torque or stiffness of the quadriceps muscle-tendon-unit (despite the increase in knee flexion). Similarly, a recent study did not report changes in tissue stiffness measured with an isokinetic dynamometer after FR at the posterior thigh, but the authors found a small decrease of shear wave velocity measured by ultrasound-elastography after FR (Morales-Artacho, Lacourpaille, & Guilhem, 2017). Also Murray et al. (2016) reported no changes in flexibility after the application of a constant stretching force, indicating no changes in passive resistance to stretch after FR. This could also explain why several authors found no decrease in performance despite an increase in ROM (Behara & Jacobson, 2015; MacDonald et al., 2013; Sullivan, Silvey, Button, & Behm, 2013). While most studies evaluating the effects of static stretching on passive stiffness show a decrease of stiffness at the hamstrings (Magnusson et al., 1995; Nordez et al., 2006; Reid & McNair, 2004; Whatman et al., 2006), there is only one study evaluating the influence of static stretching on the stiffness of the quadriceps muscle (Stafilidis & Tilp, 2015). Similar to our results, the authors did not detect changes in passive stiffness after static stretching of the anterior thigh. These findings support our results, indicating no change of dynamic passive stiffness after FR or static stretching of the quadriceps muscle tendon unit. Similar to the measurement setup used by Stafilidis and Tilp (2015), participant positioning in the current study did not allow assessment of passive stiffness in the terminal ROM. It is plausible that changes in passive stiffness after soft tissue treatments only occur in the end position. This should be considered in interpretation of our results. In addition, longer durations of stretching or FR might affect passive tissue properties (McHugh & Cosgrave, 2010).

We measured stiffness by means of the tissues response to a stretching force. Other proposed methods asses the tissues response to a compressive force (Kerins, Moore, Butterfield, McKeon, & Uhl, 2013; Wilke & Banzer, 2014) and might therefore measure different tissue properties that could potentially be altered by FR. Interestingly, Wilke, Niemeyer, Niederer, Schleip, and Banzer (2019) found a decrease in compressive stiffness at the anterior thigh after FR, so the mechanisms for changes in ROM after FR or stretching might differ.

4.3. Stretch sensation

The angle of first stretch sensation was significantly altered after both FR and stretching. This indicates that the perception of stretch shifted to a higher knee flexion angle or a higher degree of stretch of the quadriceps. Similar effects have been described after static stretching of the posterior thigh (Cabido et al., 2014; Halbertsma & Goeken, 1994; Halbertsma et al., 1996). Neurophysiological adaptations, such as an increased stretch tolerance (Behm, Blazevich, Kay, & McHugh, 2016; Magnusson et al., 1996) or changes in perception of stretch (Chaouachi et al., 2017) have been proposed as driving factors of increases in ROM after stretching. Since forces necessary to alter the structure of dense connective tissues (such as the fascia lata) by far exceed the amount of pressure utilized in FR (Chaudhry et al., 2008), several authors assume that neurophysiological mechanisms are responsible for the acute effects observed after myofascial therapies (Schleip, 2003; Simmonds, Miller, & Gemmell, 2012). Our results partly corroborate these assumptions and suggest that neuronal mechanisms play a significant role for increases in ROM after FR, likewise.

4.4. Fascial sliding

Foam rolling further influences the sliding properties of independent fascial layers. Acute changes in overall mobility of the thoracolumbar fascia has been demonstrated after FR application to various muscles around the lumbar region (Griefahn et al., 2017). Unfortunately, Griefahn et al. (2017) only reported movement of the entire fascia and not of individual layers. Further, decreased shear strain of the thoracolumbar fascia has been demonstrated in patients with nonspecific low back pain (Langevin et al.,

2011). However, different tissue properties of the thoracolumbar fascia and the fascia lata as well as different outcome parameters hinder comparability of the results. While movement of the superficial layer of the fascia lata remained constant in comparison to baseline, movement of the deep layer decreased after FR application, resulting in reduced intrafascial sliding. These changes exceed the SEM values of the measurement technique by about 12% regarding the deep layer movement, and by more than 130% regarding the intrafascial sliding. It can therefore be inferred that the observed effects were not due to the used assessment technique. Since muscle stretch was standardized in terms of movement velocity and angle, muscular movement remained virtually constant during all experimental trials. Our results point towards a decoupling between movement of the deep fascial layer and the underlying muscle after FR. An increased gliding in the interface between the fascia lata and the muscle, respectively its epimysium might in turn account for the decreased movement of the deep fascial layer. It has been shown that loose connective tissue is not only located between fascial layers, but also between the deep layer and the epimysium (Pavan, Stecco, Stern, & Stecco, 2014). Application of pressure has been proposed as a possible method to disperse adhesions between fascial layers (Martinez Rodriguez & Galan del Rio, 2013; Tozzi, 2012) and thereby improve fascial mobility. Further, compression during FR could potentially alter the viscosity of the loose connective tissue between the deep fascial layer and the muscle by changing the electromagnetic charge of collagen and proteoglycans within the extracellular matrix as well as its thixotropic properties (Barnes, 1997), leading to increased mobility. Also temporary tissue dehydration induced by the compression and rolling motion with a concurrent rehydration of the fascia or the loose connective tissue between fascia and epimysium might play a role in changes of fascial mobility (Schleip & Müller, 2013). However, as we did neither measure viscosity of loose connective tissue nor tissue hydration, these assumptions are of rather speculative nature. In addition, these concepts are more suitable to explain long-term rather than acute effects as evaluated in this study (Schleip, 2003). Further, possible alterations in viscosity of the loose connective tissue were not sufficient to decrease stiffness of the entire muscle-tendon-unit. It might however be possible that enhanced sliding between muscle and fascia might contribute to increases in ROM.

4.5. Practical implications

The results encourage utilizing FR as a tool to improve ROM in warm-up procedures before competition as neuromuscular performance is supposable not affect by FR. Since passive stiffness was not altered but the angle of first stretch sensation shifted into a higher degree of stretch, FR could be integrated into exercise and training programs where increased ROM without alterations of passive stiffness is desired, such as in speed and power dominated competitive sports. Contrary, acute changes in stiffness have been proposed as possible mechanisms to reduce muscle strain injury (Behm, Cavanaugh et al., 2016; Ryan et al., 2008). Longer durations of FR might be necessary to alter passive stiffness and thereby affect injury risk. The modification of intra-fascial sliding might also be beneficial for patients where alterations in connective tissue seem to contribute to the underlying pathology (Langevin et al., 2009, 2011; Stecco, Meneghini, Stern, Stecco, & Imamura, 2014).

Some limitations of the study have to be addressed. The chosen position allowed simultaneous measurement of most outcome parameters in one setup. However, similar to the position utilized by Stafilidis and Tilp (2015), our testing position did not allow measurement of stiffness in the terminal knee flexion angle. Future study is warranted to reveal if FR or stretching affect stiffness of the anterior thigh at the end ROM. Additionally, the position did not always produce a perceived stretch sensation in participants with high ROM.

5. Conclusions

In conclusion, the results of the present study indicate that static stretching as well as FR have an impact on active and passive ROM. Concerning the underlying mechanisms, both neurophysiological (stretch sensation) and morphological mechanisms (fascial mobility) might be responsible for acute increases in ROM after FR, while the impact of FR on passive tissue resistance or stiffness warrants further investigation. The mechanisms by which FR might alter fascial sliding and mobility as well as the long-term effects of FR have to be further explored.

The present findings encourage the use of FR as a tool to improve flexibility. However, our study suggests further indications for future research. The impact of FR on passive stiffness at other muscle groups (such as the hamstrings) remains unclear. In addition, there are several proposed mechanism leading to altered sliding of fascial layers, which merit further investigation. Since we included only healthy participants with no musculoskeletal disorders or history of injury to the lower extremity during the last twelve months, the transfer of the current results into possible treatment options for patients with dysfunctions of myofascial tissues or chronic myofascial pain remains to be elucidated. Future studies should further evaluate the impact of FR on passive tissue properties to other muscle groups, such as the hamstrings or the calf muscles, as well as the transfer of the current results into treatment options for patients with dysfunctions of myofascial tissues or chronic myofascial pain.

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Appendix A. Supplementary data

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