Heliyon 10 (2024) e39023

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Acute local and non-local morphological, sensory and fluid responses to stretching and foam rolling in young females

Ewan Thomas[a], Antonino Scardina[a,*], Antonino Patti[a], Pascal Izzicupo[b], Masatoshi Nakamura[c], Andreas Konrad[d], Francesco Campa[e], Marianna Bellafiore[a], Antonino Bianco[a]

[a] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Palermo, Italy
[b] Department of Medicine and Aging Science, "G. D'Annunzio" University of Chieti-Pescara, Chieti, Italy
[c] Faculty of Rehabilitation Sciences, Nishi Kyushu University, Kanzaki, Saga, Japan
[d] Institute of Human Movement Science, Sport and Health, University of Graz, Graz, Austria
[e] Department of Biomedical Sciences, University of Padua, Padua, Italy

ARTICLE INFO

Keywords:
L-BIA
EIM
Foam roller
Drop jump
Pain sensitivity

ABSTRACT

Background: This study aimed to compare and examine the local and non-local effects of a foam rolling (FR) and static stretching (SS) intervention applied to the plantar flexor (PF).

Methods: Fourteen female participants were investigated. Each participant underwent three conditions in a random order at least 48h apart and at the same time of the day: Control (CC), SS, and FR. Each condition was performed unilaterally in the dominant PF for 4 sets (apart from CC). SS was performed for 30 s. The FR included 30 rolls (15 in each direction) over a period of 30 s. A rest of 30 s was provided between each set for all conditions. Outcome variables were ankle dorsiflexion range of movement (ROM), tissue hardness, localized bioimpedance analysis at 50 kHz (L-BIA), and pain pressure thresholds (PPT). Tissue hardness, L-BIA, and PPT were measured in the lower leg and thigh. Measures were assessed pre (T0), immediately post (T1), and 10-min after (T2) the intervention.

Results: No differences were found for time for the CC or between the T0 of each condition. Concerning the lower leg, ROM improved for SS and FR from T0 to T1 while returning to baseline in T2. A significant increase in PPT was observed only for SS in T1. L-BIA showed a significant increase for both phase angle and impedance only for FR in T1. Tissue hardness did not change for any group at any time-point. Concerning the thigh, no measure at any time point showed significant differences.

Conclusion: Both, FR and SS were able to acutely improve ankle ROM. The observed changes were probably caused by a change in viscoelastic properties and local pain perception, without any variation in tissue morphology. FR was the only intervention to improve the intracellular-to-extracellular ratio and decrease fluids. Non-local effects were not observed.

---

[*] Corresponding author.
E-mail address: antonino.scardina01@unipa.it (A. Scardina).

https://doi.org/10.1016/j.heliyon.2024.e39023
Received 20 May 2024; Received in revised form 4 October 2024; Accepted 4 October 2024

1. Introduction

Static stretching (SS) and foam rolling (FR) are two techniques that are frequently applied to improve ROM of a joint, either after acute and chronic settings, or as warm-up strategies [1,2]. Concerning their acute effect on ROM, both techniques can be considered equally effective [2].

The ROM improvements observed following both techniques may be ascribed to different physiological mechanisms. These encompass morphological changes, a modification of pain sensation, increased body temperature, or a modification of the viscoelastic properties of tissues [3,4]. Regarding morphological changes, prior studies [5–8], exhibit heterogeneity, likely influenced by factors such as the duration and intensity of stretching or rolling, as well as the anatomical location of the applied intervention. More consistent results are observed regarding the modification of pain sensation [9,10] which can be measured as an increase in pain pressure thresholds (PPT). These increases are generally observed alongside with increases in ROM. Nevertheless, most studies focus on assessing acute post-intervention effects [8,10]. However, when examining the time-course of ROM and changes in pain sensation, heterogeneity is again observed. For instance, concerning FR interventions, Kasahara et al. [11] in a first study observed that ROM improved following a FR intervention up to 30 min, while PPT remained elevated only for 10 min. Conversely, in a second intervention [12] ROM improved up to 10 min while PPT remained elevated for 15 min. Similarly to FR interventions, also in SS, the time-course measures of PPT may or may not correspond to the variations in ROM in measures other than those immediately post-exercise [13,14]. These findings indicate that both morphological variations and modifications in pain sensation may contribute, albeit not exclusively, as underlying mechanisms for the improvement in ROM. Recent evidence [15] has observed that following a FR intervention, improvements in ROM were also observed when sham rolling was applied (i.e., just mimic the movement of FR while no pressure on the target tissue). These results, together with those of other investigations [16–18], would suggest that ROM can also improve through a warm-up effect. It is interesting to note that following both FR and SS interventions, an increase in local temperature can be observed [19,20].

To date, only one study has evaluated the effects of a FR intervention concerning local tissue fluid hydration (using a localized bioimpedance analysis (L-BIA), also defined Electrical Impedance Myography (EIM) [21,22] a procedure that allows to identify raw bioelectrical parameters in specific body segments. This allows to identify Phase Angle (PhA) and vector length (Z) which are related to fluid distribution and fluid quantity [23,24], respectively), which could be other factor influencing the viscoelastic properties of tissues., Within the study of Yoshimura et al. [19] applying FR on the plantar flexor muscle, the authors concluded that a reduction in the fluid content of the leg was observed. Such effects were more pronounced in women. It is interesting that an increase in temperature was also observed, indicating a potential relation between the warm-up effect and the variation in fluid dynamics. It is, however, still to clarify if improvements in ROM following the FR are due to the mechanical pressure of the roller over the muscle belly or an increase in local temperature. Conversely, no studies have evaluated the effects of a SS intervention on local fluid variations.

Furthermore, there has been recent interest in investigating non-local effects (when interventions are applied to an anatomical location and effects are measured elsewhere) alongside the traditional local effects [25,26]. However, the majority of these studies take into consideration the non-local effects of the homologous muscle groups in the contralateral limb, namely the "*crossover effect*" [26]. Very few investigations, which have also provided heterogeneous results, have evaluated non-local effects in contiguous body segments (i.e. interventions carried out on the plantar fascia and effects measured in the plantar flexor muscles [27]) or segments encompassed within a myofascial chain [28,29]. In addition, despite previous research that has evaluated the effects of FR on local fluid distribution [19] observing its reorganization, there is a gap in research on the fluid dynamics of continuous body segments. Therefore, it still remains unclear whether the reorganization of these fluids may be directed towards the surrounding tissues, the bloodstream, or tissues in other body segments.

Thus, this study aimed to examine the acute effects of four sets of 30 s of SS and FR interventions carried out in the PF muscles and examine either local (where the intervention was administered) and non-local (the adjacent lower limb compartment [the thigh]) morphological, sensory, and fluid responses as potential determinants of ROM improvement. The intervention was carried out in women since these tend to have lower body water content compared to men.

2. Materials and methods

2.1. Participants

Fourteen healthy female participants were enrolled (the descriptive characteristics of the participants are shown in Table 1). The required sample size was calculated through G-power (G*Power version 3.1.9.4) for a repeated measure ANOVA (F-Tests effect size = 0.25, α error = 0.05, and power = 0.80) considering 3 groups (CC, SS, and FR) and 3 time-points (T0, T1, and T2) based on our previous

Table 1
Descriptive characteristics of participants.

	F
N	14
Age	22.3 ± 2.7
Weight (kg)	59.6 ± 8.78
Height (cm)	161.6 ± 8.77

study's ROM results [11] was more than 10 participants. Participants were recruited from a population of university students. All participants had to be free of orthopaedic, neurological, and gynaecological diseases. If participants had a previous history of injuries to the lower limbs, were excluded, as were those taking oral contraceptives. A total of three women were excluded priorly. Participants could take part in the experiment only during the follicular phase of their menstrual cycle [30,31] in order to standardise bodily fluid balance. All participants had to refrain from using coffee or drinking water for at least 30 min before the experiments in order to further standardise bodily fluids across conditions. In order to take part in the study, all participants had to sign a written informed consent, in which the study protocol along with the risks and benefits of participating in the experiment, were disclosed. The study was approved by the bioethical committee of the University of Palermo (protocol n°170/2023). Research was conducted in accordance with the Helsinki Declaration and the European Union recommendations for good clinical practice.

2.2. *Procedure*

Participants were asked to attend our laboratory on three occasions, at least 48 h apart, at the same time of the day. During each visit, the temperature of the laboratory was controlled at 24 °C. On each visit, participants were randomised to one of the following conditions: Control condition (CC), SS, or FR. Each participant, during each visit, was tested three times: upon arrival (T0), immediately after each intervention (T1), and after 10 min from the end of the intervention (T2). During the CC, no intervention was administered to the participants, who were instructed to sit on a chair for 10 min after the T0 assessment. Each participant between T1 and T2 was instructed to sit on a chair. At each time-point a measure of ankle ROM dorsiflexion was assessed. In addition, measures of tissue hardness (TH) and pain pressure threshold (PPT) were assessed in the medial gastrocnemius, the biceps femoris, and the semitendinosus, along with a localised bioimpedance analysis (L-BIA) in the lower leg and thigh. Since dynamic activities such as ROM may influence TH, PPT, and L-BIA, these were assessed prior to ROM. Consequently, the order of each assessment was TH, PPT, L-BIA, and ROM. The reproducibility of this method was confirmed in a previous [11] study. All the above-mentioned measures were collected on the dominant limb, which was the right leg for all participants. Dominance was assessed by asking each participant with which leg they would kick a ball.

2.3. *Outcomes*

All measures were collected three times at each time point by the same investigator except for the L-BIA which was measured once.

2.3.1. *Range of movement*

ROM of the ankle was assessed in a dorsiflexion motion for the plantar flexor muscle in each participant. Each participant was placed on a medical bed in a prone position with the knee extended, with inelastic straps positioned on the pelvis and the contralateral leg in order to avoid compensatory movements. A flat, rigid surface was then strapped to the sole of the foot of each participant. A two-arm electronic goniometer (Digital Angle Ruler, resolution 0.05°, accuracy ±0.2°, repeatability 0.05°) was then placed with one arm parallel to the foot sole and one arm parallel to the leg. In order to improve the reliability of each measure, the goniometer position was standardised by applying visual marks to the skin of each participant using a dermal marker. The assessment started when the foot and leg formed a 90° angle. The maximum tolerable pain for each participant, or the limit of available ROM [32,33] during each assessment, was the final value retained for each assessment. Of the three collected measures for each assessment, the mean value was used for analysis.

2.3.2. *Tissue hardness*

A portable TH metre (NEUTONE TDM-N1; TRY-ALL Corp., Chiba, Japan) was used for data collection. This TH metre measures the penetration distance until a 14.71 N (1.5 kgf) pressure is reached [34]. Measures of TH were collected in the medial gastrocnemius (MG) for the lower leg, the bicep femoris (BF), and the semitendinosus (ST) for the thigh. Each participant was asked to lie prone on a medical bed. Concerning the measures of the MG, a mid-point between the popliteal fossa and the proximal end of the Achilles's tendon was evaluated. For the BF and the ST, the proximal and distal reference points were the ischiatic tuberosity and the popliteal fossa, respectively. Two mid-points between these reference points were considered. A lateral point for the BF and a medial point for the ST. Each point was marked with a dermal marker to improve the reliability of the measures. During each assessment, participants were asked to relax. Of the three collected measures for each assessment at each point, the mean value was used for analysis.

2.3.3. *Pain pressure thresholds*

A portable algometer (FPX 25 Pain Tester, Wagner Instruments, CT, USA) was used to assess PPT. The participant's measurement position and evaluated points were identical to the TH assessment. The algometer was positioned perpendicular to the direction of the muscle fibers. A pressure of 1 kg per second was applied by the investigator. Each participant was instructed to say "stop" when pain, rather than just pressure, was experienced. The final value reported on the screen of the instrument, measured in kg•cm2 was considered a PPT. Of the three collected measures for each assessment at each point, the mean value was used for analysis.

2.3.4. *Localized bioimpedance analysis*

A single-frequency phase-sensitive device (BIA-101 Anniversary Sport Edition, Akern Systems, Firenze, Italy) at 50 kHz and 400 μA was used to measure phase angle (PhA) and bioimpedance (Z) [35] of the lower leg and thigh. Two pairs of electrodes (source (I) and detector (V) electrodes) for each body segment were used. For the lower leg, one pair was positioned on the upper part of the lower leg, with the lateral part of the I positioned on the popliteal crease and the V positioned distally, parallel to the I, 5 cm apart. The other pair was positioned on the lower part of the lower leg, with the lateral part of the I positioned above the tibial malleolus and the V in a proximal direction parallel to the I, 5 cm apart. For the thigh, one pair of electrodes was positioned on the upper part of the thigh with the lateral part of the I above the distal end of the ischiatic tuberosity and the V in a distal direction, 5 cm apart. The other pair was positioned with the lateral part of the I on the popliteal crease and the V positioned proximally, parallel to the I, 5 cm apart. Reference points were marked on the skin of the participants using a dermal marker to allow repeatability of the positioning of the electrodes (Fig. 1). The lower leg and thigh assessments were not performed simultaneously.

Z was standardised for each body segment according to segment length. Lower leg length was calculated in cm, from the popliteal crease to the mid-point of the tibial malleolus. Thigh length was calculated in cm, from the popliteal crease to the ischial tuberosity (Fig. 1). Prior to each test, the BIA measurements of the analyser were validated using a precision circuit with acceptance for resistance (R) measurements of 383 Ω (Ω) and reactance (Xc) values of 45 Ω. Coefficient of variation for PhA and Z were calculated on the T0 of all conditions, these being 2.88 and 1.37 for the leg and 4.17 and 3.18 for the thigh, respectively.

2.4. *Interventions*

A SS and a FR intervention were administered to the dominant PF of each participant. Each intervention was administered in four sets, with a 30-s rest between each set. The intensity of each intervention was controlled by asking each participant to feel the SS or the pressure of the FR at a magnitude of at least 8 out of a scale from 0 to 10. The adopted roller was a low-cost, commercially available roller (Bodymate, 30 cm in length, 15 cm in diameter in expanded polypropylene foam of medium density with a GRID surface). These characteristics were chosen following the recommendations suggested by previous research [36,37]. Familiarization for each intervention was allowed on the contralateral limb to understand either body position and intensity. Each aspect had to be familiarized separately. A maximum of 5 s of SS and a maximum of five rolls with the FR were allowed for such purposes in order to limit potential non-local contralateral effects [26,38]. For the SS, each participant was asked to stand upright and position their foot over a 35° inclined wedge for 30 s for each set. Each participant could adjust their body position to reach the required intensity. For the FR, the participants had to place the muscle belly of the PF over the GRID pattern of the roller. For each set, the participants had to roll the muscle belly 15 times in a proximal direction and 15 times in a distal direction over the roller. Each roll in each direction had to last 1 s, for a total time per set of 30 s. Rolling time was controlled through a metronome sound produced by a mobile device app (Metronomo: Tempo lite ver. 5.0.7, App Store, Apple). No intervention was applied to the knee flexors.

2.5. *Statistical analysis*

Means ± standard deviations were used to present the results. Intraclass correlation coefficients (ICC) were calculated from the T0 for all measures to check the reliability of the measures. ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 indicate poor, moderate, good, and excellent reliability, respectively [39]. An analysis of variance (ANOVA) for repeated measures for time and groups was used to identify differences for the main variables. Post-hoc Scheffé corrections were performed when the main variables showed a significant time-x-group interaction to identify sub-group and time differences. For each main analysis, the effect size (ES) was calculated. Partial eta squared (η2p) was used as a measure of ES. The magnitude of the ES was classified according to the following scale: 0.01–0.059 = small effect, 0.06–0.139 = moderate effect, and ≥0.14 = large effect. All analyses were performed with Jamovi (The Jamovi Project, 2021). Jamovi (Version 2.3.12.0)[Computer Software]. Retrieved from https://www.jamovi.org. Significance was considered <0.05 for all analyses.

3. Results

No baseline differences (T0) were observed among interventions (CC, SS, and FR) for all investigated variables (ROM, TH, PPT, PhA, and Z) in either the lower leg or thigh.

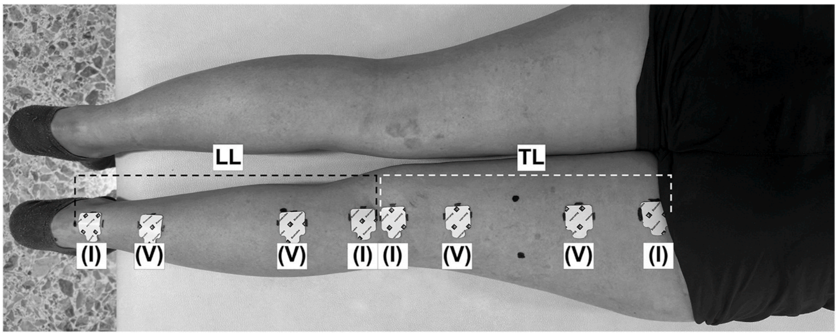

Fig. 1. Graphical representation of electrode placement and setting for the localized bioimpedance analysis.
LL: Lower leg length; I: Source electrode; TL: Thigh length; V: Detector electrode;.

3.1. Local measures

ICC for ROM was 0.96. The ICCs for TH, PPT, PhA, and Z of the leg were 0.86, 0.91, 0.95, and 0.99, respectively. Concerning measures of the lower leg, a significant time × group interaction was observed for ROM, PPT, PhA, and Z (Table 2). Post-hoc Scheffé analysis showed differences among interventions. In particular, ROM improved for both SS and FR from T0 to T1 while returning to baseline in T2. Only for SS, the increase in ROM was accompanied by an increase in the measure of PPT from T0 to T1. Only for the FR, the increase in ROM was accompanied by an increase of both Z and PhA from T0 to T1.

3.2. Non-local measures

The ICCs for TH BF, PPT BF, TH ST, PPT ST, PhA, and Z of the thigh were 0.81, 0.83, 0.90, 0.86, 0.95, and 0.96, respectively. Concerning measures of the thigh, no significant interaction was observed for any analyzed variable (Table 2).

4. Discussion

The present manuscript aimed to understand the effects of an SS and FR intervention on morphological, sensory, and fluid responses measured locally, where the intervention was applied, and non-locally, in the adjacent body segment. Our results indicate that both interventions were able to improve local ROM. However, notwithstanding not observing differences in morphological responses, there were differences concerning sensory and fluid responses. In particular, SS was accompanied by an increase in measures of PPT, while FR was accompanied by an increase in PhA and Z. The observed effects were only present locally, without any variation, for any measured variable in the adjacent body segment. These results suggest that, following SS, decreased pain sensitivity is the main contributor to ROM improvement. While for FR, a variation in both fluid quantity (Z) and intracellular-to-extracellular fluid ratio (PhA), which may modify the viscoelastic properties of the tissue, appears to be the main contributors to ROM improvement.

In the present investigation, we did not appreciate any variation in TH, neither in the PF or knee flexor muscles. Concerning the PF, which were those targeted by the SS and FR interventions, our results seem in line with previous investigations [5,40,41]. Despite a certain degree of heterogeneity among interventions in which variations in TH might be present [5], a more in-depth glance highlights that variations in TH, specifically in the PF, do not appear significant across studies. In addition, changes in TH seem to be time-dependent, with longer interventions eliciting the greatest variations. Within the present investigation, we provided for both SS and FR a volume of 120 s. Such volume, according to Takeuchi et al. [5], seems to be the one eliciting the fewest variations. Concerning the BF and ST in the thigh, again, we did not observe any variation. To date, no previous study has acutely evaluated the effects of an intervention on the TH of the thigh muscles while providing the intervention to muscles of the lower leg. However, a similar approach among continuous body segments, although considering chronic effects, has been carried out by Konrad et al. [27]. The authors

Table 2
Synthesis of outcomes of ROM, TH, PPT and L-BIA for each condition and body segment.

	CC			SS			FR			ANOVA
	T0	T1	T2	T0	T1	T2	T0	T1	T2	Time x Group
Leg (local)										
ROM(°)	36.7 ± 5.62	37.1 ± 5.63	37.5 ± 6.04	36.0 ± 5.56	40.3 ± 4.98§	38.2 ± 5.04$^{╪}$	35.2 ± 5.13	38.5 ± 4.63§	37.0 ± 4.61	*p=<0.0001; F = 8.27; η^2p = 0.298
TH(N)	23.9 ± 2.97	23.2 ± 3.09	23.0 ± 3.40	23.7 ± 2.22	21.9 ± 3.18	22.2 ± 3.24	23.0 ± 2.69	21.6 ± 3.79	22.2 ± 3.76	p = 0.44; F = 0.94; η^2p = 0.046
PPT(KG)	4.63 ± 1.73	4.77 ± 1.31	4.96 ± 1.66	4.87 ± 1.16	5.77 ± 1.57§	5.15 ± 1.56	4.49 ± 1.18	4.93 ± 1.20	5.17 ± 1.54	*p = 0.03; F = 2.79; η^2p = 0.125
PhA(°)	11.7 ± 1.44	11.5 ± 1.43	11.4 ± 1.58	11.6 ± 1.47	11.5 ± 1.47	11.5 ± 1.44	11.6 ± 1.17	12.1 ± 1.36§	11.9 ± 1.37	*p = 0.0007; F = 5.37; η^2p = 0.216
Z(Ω)	1.43 ± 0.22	1.41 ± 0.23	1.41 ± 0.23	1.44 ± 0.27	1.43 ± 0.26	1.42 ± 0.26	1.41 ± 0.22	1.46 ± 0.23§	1.44 ± 0.23	*p = 0.0007; F = 5.40; η^2p = 0.217
Thigh (non-local)										
TH BF (N)	17.5 ± 3.03	17.0 ± 3.32	16.1 ± 2.85	18.5 ± 2.27	17.3 ± 2.18	16.7 ± 2.95	17.9 ± 3.38	16.8 ± 3.04	17.3 ± 3.00	p = 0.29; F = 1.27; η^2p = 0.061
PPT BF (KG)	6.50 ± 1.60	6.83 ± 1.76	6.91 ± 1.97	6.61 ± 1.39	7.34 ± 2.11	7.51 ± 2.15	6.30 ± 1.36	7.14 ± 1.76	7.30 ± 2.18	p = 0.40; F = 1.03; η^2p = 0.051
TH ST (N)	15.7 ± 3.45	15.7 ± 2.77	15.1 ± 3.66	15.6 ± 3.59	15.8 ± 3.80	14.6 ± 3.66	16.0 ± 4.04	15.5 ± 4.70	16.0 ± 4.27	p = 0.22; F = 1.47; η^2p = 0.070
PPT ST (KG)	6.24 ± 1.96	6.84 ± 1.91	6.49 ± 1.54	6.13 ± 1.45	7.08 ± 2.18	7.12 ± 2.01	5.96 ± 1.60	6.58 ± 1.61	6.87 ± 1.72	p = 0.47; F = 0.89; η^2p = 0.045
PhA(°)	10.4 ± 1.88	10.0 ± 2.03	10.2 ± 2.09	10.9 ± 1.93	10.5 ± 1.73	10.5 ± 1.92	10.7 ± 1.99	10.6 ± 2.08	10.6 ± 1.79	p = 0.44; F = 0.93; η^2p = 0.046
Z(Ω)	1.11 ± 0.22	1.08 ± 0.19	1.07 ± 0.19	1.06 ± 0.19	1.04 ± 0.16	1.04 ± 0.16	1.04 ± 0.16	1.03 ± 0.15	1.03 ± 0.15	p = 0.37; F = 1.08; η^2p = 0.052

Data are presented as means ± SD; T0: Baseline Evaluation; T1: Post-test assessment; T2: Assessment 10m post-test; BF: Biceps Femoris; CC: Control Condition; FR: Foam Rolling; PhA: Phase Angle; PPT: Pain Pressure Thresholds; SS: Static Stretching; ST: Semitendinosus; TH: Tissue Hardness; Z: Impedance. ANOVA: Analysis of Variance.*:Significant $p < 0.05$, §: different from T0, ╪: T2 different from T1.

applied combined SS and FR training to the plantar foot sole for 7 weeks and observed responses in the PF muscles. Despite observing a tendency of an increase in ROM, no variation in muscle structure was observed in the PFs despite the longer intervention, which, similar to the present investigation, represents the adjacent body segment.

The improvement in ROM in the present investigation was accompanied by an increase in measures of PPT only for SS. Such a concomitant increase was observed only from T0 to T1, while returning to baseline in T2 indicating a variation of local pain sensitivity. No variation in PPT was observed following the FR intervention. This result does not appear in line with previous investigations [10, 42]. Within this study only female participants were included, therefore our results may vary according to the screened population. However, there is heterogeneity in findings considering sex differences in pain perception [43–45]. Another possible explanation may arise from the investigations of Warneke et al. [15,16] indicating improvements in ROM following several warm-up strategies including sham-rolling but also interventions different than FR, which would indicate that a possible warm-up effect rather than a modification of pain sensitivity could be an additional factor contributing to improving ROM following FR. Variations in PPT were not observed in the muscles of the thigh, suggesting, especially for SS, in which a variation in the PF was present, that pain perception was modulated locally rather than as a modulation of the endogenous pain inhibitory system [46].

Only following the FR intervention, we observed a variation in the parameters of the L-BIA. In particular, from T0 to T1, an increase in the PhA and Z values was observed. The action of FR appears to lead to a reduction in leg water, particularly in the extracellular compartment, as indicated by the increase in Z and PhA. Indeed, Z is inversely correlated with water content, while PhA is positively correlated with the intracellular-to-extracellular water ratio. However, while the total water in the leg decreases, no variation is observed in thigh water. Therefore, it seems that the action of FR results in the redistribution of fluids into the cells and towards vessels that would still transport water to the central areas of the body. Our results are similar to those of Brandl and Yoshimura et al. [19,47]. In the study of Yoshimura et al. [19], the author observed that following a FR intervention, local impedance increased. Similar results were observed by Brandl et al. [47] after applying instrument-assisted soft tissue mobilization to the lumbar fascia, in which again an increase in values of impedance was observed. Altogether, the results of previous investigations suggest that a FR intervention may determine local fluid variations. However, from the data of such research, it was not possible to infer more precise mechanisms. In the present investigation, we observed a concomitant increase in PhA and Z, which indicate an improvement of the intracellular-to-extracellular ratio and a decrease in the total amount of fluids, respectively [24]. Extracellular water represents plasma and interstitial fluids, while intracellular water represents muscle cell mass [48]. Increased intracellular water content appears to be an indicator of improved performance, muscle quality, and reduced frailty [49–51]. Conversely, an increase in extracellular water is associated with inflammation, sarcopenia, muscle wasting, malnutrition, and disease [52]. If we consider that we observed an increase in Z, therefore indicating a decrease in the total amount of water [35], it is plausible that the major contributor to the improved intracellular-to-extracellular ratio is a decrease in extracellular water. However, considering the viscoelastic properties of biological tissues, which also depend on tissue hydration [53,54] a decrease in the water content would logically lead to a more rigid tissue. Therefore, we hypothesise that a concomitant decrease of extracellular fluids with an increase in intracellular fluids occurred, improving muscle efficiency [55] and therefore, ROM. The effect observed may open to possible new applications of the FR as a tool to locally reduce extracellular fluids in those conditions characterized by fluid accumulation.

We acknowledge that the present study may have some limitations. First, our measures of PPT were evaluated through a portable algometer, which was stopped by a verbal command from the participant. Such a procedure may have overestimated the measured parameter. However, the reliability of such measures for the lower leg and thigh is high (ICC = 0.91, 0.83, and 0.86). In addition, despite equalizing both interventions for intensity and volume, there is the need in future investigations to find a more physiologically oriented variable for standardization. In the present investigation we adopted a L-BIA which provides us the possibility to measures local tissue impedance, however, such approach does not allow us to estimate water quantities. Further, despite all participants declared to be active by regularly exercising, we did not screen for individual activity levels. Lastly, our analyzed sample was composed solely of women,; therefore, results may differ for men. Despite such limitations, women are an underrepresented sample in the field of sports medicine [56], and have in general a lower water content and greater extracellular water quantities than men [57] (if weight is normalized). Therefore, we believe the choice of evaluating fluid response in females may simultaneously be a limit and a strength of this study. This study is the first to include a measure of L-BIA following SS and FR in the investigated and adjacent body segments.

5. Conclusions

SS and FR were both able to acutely improve ROM. The effects of both interventions could be appraised locally without any modification of any assessed outcome in the adjacent body segment. SS improved ROM through a modification of pain perception, while FR improved ROM through a supposed modification of the viscoelastic properties of tissues. No difference in tissue morphology was observed for any group.

Only following the FR, a local increase in the intracellular-to-extracellular ratio of the leg and a decrease in total fluid content was observed. Collectively, these findings suggest that FR may serve as a potential strategy for promptly alleviating water retention in targeted body segments.

CRediT authorship contribution statement

Ewan Thomas: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Antonino Scardina:** Data curation. **Antonino Patti:** Data curation. **Pascal Izzicupo:** Writing – review & editing. **Masatoshi Nakamura:** Writing – review & editing. **Andreas Konrad:** Writing – review & editing. **Francesco Campa:** Writing – original draft. **Marianna Bellafiore:** Writing –

review & editing. **Antonino Bianco:** Validation, Supervision.

Ethics approval statement

The study was approved by the University of Palermo bioethical committee (protocol n°170/2023).

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Data availability statement

Data will be made available on request.

Funding

No funding was used during the preparation of this manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations:

BF	Bicep Femoris
CC	Control group
FR	Foam Roller
I	source
L-BIA	Localized Bioimpedance Analysis
MG	Medial Gastrocnemius
PF	Plantar Flexor
PhA	Phase Angle
PPT	Pain Pressure Threshold
R	Resistence
ROM	Range of Motion
SS	Static Stretching
ST	Semitendinosus
TH	Tissue Hardness
V	Detector
Xc	Reactance
Z	Bioimpedence

References

[1] K. Small, L. Mc Naughton, M. Matthews, A systematic review into the efficacy of static stretching as part of a warm-up for the prevention of exercise-related injury, Res. Sports Med. 16 (3) (2008) 213–231.

[2] A. Konrad, M. Nakamura, F.K. Paternoster, M. Tilp, D.G. Behm, A comparison of a single bout of stretching or foam rolling on range of motion in healthy adults, Eur. J. Appl. Physiol. 122 (7) (2022) 1545–1557.

[3] D.G. Behm, J. Wilke, Do self-myofascial release devices release myofascia? Rolling mechanisms: a narrative review, Sports Med. 49 (8) (2019) 1173–1181.

[4] C.H. Weppler, S.P. Magnusson, Increasing muscle extensibility: a matter of increasing length or modifying sensation? Phys. Ther. 90 (3) (2010) 438–449.

[5] K. Takeuchi, M. Nakamura, T. Fukaya, A. Konrad, T. Mizuno, Acute and long-term effects of static stretching on muscle-tendon unit stiffness: a systematic review and meta-analysis, J. Sports Sci. Med. 22 (3) (2023) 465–475.

[6] H. Chaabene, D.G. Behm, Y. Negra, U. Granacher, Acute effects of static stretching on muscle strength and power: an attempt to clarify previous caveats, Front. Physiol. 10 (2019) 1468.

[7] M.H. Glänzel, D.R. Rodrigues, G.N. Petter, D. Pozzobon, M.A. Vaz, J.M. Geremia, Foam rolling acute effects on myofascial tissue stiffness and muscle strength: a systematic review and meta-analysis, J. Strength Condit Res. 37 (4) (2023).

[8] K. Kasahara, A. Konrad, Y. Murakami, R. Yoshida, E. Thomas, M. Nakamura, Acute effects of different foam roller intervention techniques on knee extensors, J. Sports Sci. Med. 22 (4) (2023) 681–687.

[9] M.P. Støve, R.P. Hirata, T.S. Palsson, The tolerance to stretch is linked with endogenous modulation of pain, Scand J Pain 21 (2) (2021) 355–363.

[10] S.W. Cheatham, M.J. Kolber, Does roller massage with a foam roll change pressure pain threshold of the ipsilateral lower extremity antagonist and contralateral muscle groups? An exploratory study, J. Sport Rehabil. 27 (2) (2018) 165–169.

[11] K. Kasahara, A. Konrad, R. Yoshida, Y. Murakami, R. Koizumi, S. Sato, et al., Comparison of the prolonged effects of foam rolling and vibration foam rolling interventions on passive properties of knee extensors, J. Sports Sci. Med. 21 (4) (2022) 580–585.

[12] K. Kasahara, A. Konrad, R. Yoshida, Y. Murakami, S. Sato, R. Koizumi, et al., Comparison of Acute and Prolonged Effects of Short-Term Foam Rolling and Vibration Foam Rolling on the Properties of Knee Extensors, 2023, pp. 19–26.

[13] S. Matsuo, M. Iwata, M. Miyazaki, T. Fukaya, E. Yamanaka, K. Nagata, et al., Acute and prolonged effects of 300 sec of static, dynamic, and combined stretching on flexibility and muscle force, J. Sports Sci. Med. 22 (4) (2023) 626–636.

[14] Y. Zhu, Y. Feng, F. Huang, Y. Li, W. Wang, X. Wang, et al., Changes in stiffness of the specific regions of knee extensor mechanism after static stretching, Front. Bioeng. Biotechnol. 10 (2022) 958242.

[15] K. Warneke, J.C. Aragão-Santos, S. Alizadeh, M. Bahrami, S.H. Anvar, A. Konrad, D.G. Behm, Are acute effects of foam-rolling attributed to dynamic warm up effects? A comparative study, J. Sports Sci. Med. 22 (2) (2023) 180–188.

[16] K. Warneke, G. Plöschberger, L.H. Lohmann, E. Lichtenstein, D. Jochum, S.D. Siegel, et al., Foam rolling and stretching do not provide superior acute flexibility and stiffness improvements compared to any other warm-up intervention: a systematic review with meta-analysis, Journal of Sport and Health Science 13 (4) (2024) 509–520.

[17] K. Takeuchi, M. Takemura, M. Nakamura, F. Tsukuda, S. Miyakawa, Effects of active and passive warm-ups on range of motion, strength, and muscle passive properties in ankle plantarflexor muscles, J. Strength Condit Res./National Strength & Conditioning Association 35 (1) (2021) 141–146.

[18] R.R. Dexter, T.K. Loftis, A.N. Pettaway, R.T. Baker, J. May, The immediate effects of a total motion RELEASE® warm-up on active rotational HIP range of motion in overhead athletes, International journal of sports physical therapy 14 (6) (2019) 898–910.

[19] A. Yoshimura, Y. Sekine, R. Schleip, A. Furusyo, K. Yamazaki, T. Inami, et al., The acute mechanism of the self-massage-induced effects of using a foam roller, J. Bodyw. Mov. Ther. 27 (2021) 103–112.

[20] U.F. de Oliveira, L.C. de Araújo, P.R. de Andrade, H.H. Dos Santos, D.G. Moreira, M. Sillero-Quintana, J.J. de Almeida Ferreira, Skin temperature changes during muscular static stretching exercise, Journal of exercise rehabilitation 14 (3) (2018) 451–459.

[21] Á. Cebrián-Ponce, A. Irurtia, M. Carrasco-Marginet, G. Saco-Ledo, M. Girabent-Farrés, J. Castizo-Olier, Electrical impedance Myography in health and physical exercise: a systematic review and future perspectives, Front. Physiol. 12 (2021) 740877.

[22] L. Nescolarde, A. Talluri, J. Yanguas, H. Lukaski, Phase angle in localized bioimpedance measurements to assess and monitor muscle injury, Rev. Endocr. Metab. Disord. 24 (3) (2023) 415–428.

[23] F. Campa, C.N. Matias, E. Marini, S.B. Heymsfield, S. Toselli, L.B. Sardinha, A.M. Silva, Identifying athlete body fluid changes during a competitive season with bioelectrical impedance vector analysis, Int. J. Sports Physiol. Perform. 15 (3) (2020) 361–367.

[24] E. Marini, F. Campa, R. Buffa, S. Stagi, C.N. Matias, S. Toselli, et al., Phase angle and bioelectrical impedance vector analysis in the evaluation of body composition in athletes, Clin. Nutr. 39 (2) (2020) 447–454.

[25] D.G. Behm, S. Alizadeh, B. Drury, U. Granacher, J. Moran, Non-local acute stretching effects on strength performance in healthy young adults, Eur. J. Appl. Physiol. 121 (6) (2021) 1517–1529.

[26] D.G. Behm, S. Alizadeh, S.H. Anvar, B. Drury, U. Granacher, J. Moran, Non-local acute passive stretching effects on range of motion in healthy adults: a systematic review with meta-analysis, Sports Med. 51 (5) (2021) 945–959.

[27] A. Konrad, M.M. Reiner, A. Gabriel, K. Warneke, M. Nakamura, M. Tilp, Remote effects of a 7-week combined stretching and foam rolling training intervention of the plantar foot sole on the function and structure of the triceps surae, Eur. J. Appl. Physiol. 123 (8) (2023) 1645–1653.

[28] Wilke, D. Niederer, L. Vogt, W. Banzer, Remote effects of lower limb stretching: preliminary evidence for myofascial connectivity? J. Sports Sci. 34 (22) (2016) 2145–2148.

[29] C. Burk, J. Perry, S. Lis, S. Dischiavi, C. Bleakley, Can myofascial interventions have a remote effect on ROM? A systematic review and meta-analysis, J. Sport Rehabil. 29 (5) (2020) 650–656.

[30] F. Campa, M. Levi Micheli, M. Pompignoli, R. Cannataro, M. Gulisano, S. Toselli, et al., The influence of menstrual cycle on bioimpedance vector patterns, performance, and flexibility in elite soccer players, Int. J. Sports Physiol. Perform. 17 (1) (2022) 58–66.

[31] S. Kanellakis, E. Skoufas, E. Simitsopoulou, A. Migdanis, I. Migdanis, T. Prelorentzou, et al., Changes in body weight and body composition during the menstrual cycle 35 (11) (2023) e23951.

[32] R.Y.W. Lee, J. Munn, Passive moment about the hip in straight leg raising, Clin. Biomech. 15 (5) (2000) 330–334.

[33] Thomas, S. Ficarra, A. Scardina, M. Bellafiore, A. Palma, N. Maksimovic, et al., Positional transversal release is effective as stretching on range of movement, performance and balance: a cross-over study, BMC Sports Science, Medicine and Rehabilitation 14 (1) (2022) 202.

[34] T. Sawada, H. Okawara, D. Nakashima, S. Iwabuchi, M. Matsumoto, M. Nakamura, T. Nagura, Reliability of trapezius muscle hardness measurement: a comparison between portable muscle hardness meter and ultrasound strain elastography, Sensors 20 (24) (2020).

[35] R. Francisco, F. Jesus, C.L. Nunes, A. Carvalho, M. Alvim, F. Campa, et al., Prediction of body water compartments by raw bioelectrical impedance parameters in athletes: comparison between series and parallel measurements, Scand. J. Med. Sci. Sports 33 (10) (2023) 1998–2008.

[36] S.W. Cheatham, K.R. Stull, Comparison of three different density type foam rollers on knee range of motion and pressure pain threshold: a randomized controlled trial, International journal of sports physical therapy 13 (3) (2018) 474–482.

[37] S.W. Cheatham, K.R. Stull, Roller massage: comparison of three different surface type pattern foam rollers on passive knee range of motion and pain perception, J. Bodyw. Mov. Ther. 23 (3) (2019) 555–560.

[38] M. Nakamura, A. Konrad, R. Kiyono, S. Sato, K. Yahata, R. Yoshida, et al., Local and non-local effects of foam rolling on passive soft tissue properties and spinal excitability, Front. Physiol. 12 (2021).

[39] T.K. Koo, M.Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, Journal of chiropractic medicine 15 (2) (2016) 155–163.

[40] M. Nakamura, A. Konrad, R. Kiyono, S. Sato, K. Yahata, R. Yoshida, et al., Local and non-local effects of foam rolling on passive soft tissue properties and spinal excitability, Front. Physiol. 12 (2021) 702042.

[41] M. Nakamura, A. Konrad, K. Ryosuke, S. Sato, K. Yahata, R. Yoshida, et al., Sex differences in the mechanical and neurophysiological response to roller massage of the plantar flexors, J. Sports Sci. Med. 20 (4) (2021) 665–671.

[42] J.D. Young, A.J. Spence, D.G. Behm, Roller massage decreases spinal excitability to the soleus, J. Appl. Physiol. 124 (4) (2018) 950–959.

[43] L.S. Chesterton, P. Barlas, N.E. Foster, D.G. Baxter, C.C. Wright, Gender differences in pressure pain threshold in healthy humans, Pain 101 (3) (2003) 259–266.

[44] E. Garcia, D. Godoy-Izquierdo, J.F. Godoy, M. Perez, I. Lopez-Chicheri, Gender differences in pressure pain threshold in a repeated measures assessment, Psychol. Health Med. 12 (5) (2007) 567–579.

[45] A. Konrad, K. Kasahara, R. Yoshida, Y. Murakami, R. Koizumi, M. Nakamura, Pain-pressure threshold changes throughout repeated assessments with No sex related differences 11 (4) (2023) 475.

[46] M.P. Støve, R.P. Hirata, T.S. Palsson, Muscle stretching - the potential role of endogenous pain inhibitory modulation on stretch tolerance, Scand J Pain 19 (2) (2019) 415–422.

[47] A. Brandl, C. Egner, M. Schwarze, R. Reer, T. Schmidt, R. Schleip, Immediate effects of instrument-assisted soft tissue mobilization on hydration content in lumbar myofascial tissues: a quasi-experiment, J. Clin. Med. 12 (3) (2023).

[48] C. Iwasaka, Y. Yamada, Y. Nishida, M. Hara, J. Yasukata, N. Miyoshi, et al., Association of appendicular extracellular-to-intracellular water ratio with age, muscle strength, and physical activity in 8,018 community-dwelling middle-aged and older adults, Arch. Gerontol. Geriatr. 108 (2023) 104931.

[49] A.M. Silva, C.N. Matias, D.A. Santos, P.M. Rocha, C.S. Minderico, L.B. Sardinha, Increases in intracellular water explain strength and power improvements over a season, Int. J. Sports Med. 35 (13) (2014) 1101–1105.

[50] M. Tian, J. Yuan, F. Yu, P. He, Q. Zhang, Y. Zha, Decreased intracellular water is associated with sarcopenic obesity in chronic haemodialysis patients, BMC Geriatr. 23 (1) (2023) 630.

[51] M. Serra-Prat, I. Lorenzo, E. Palomera, J.C. Yébenes, L. Campins, M. Cabré, Intracellular water content in lean mass is associated with muscle strength, functional capacity, and frailty in community-dwelling elderly individuals. A cross-sectional study, Nutrients 11 (3) (2019).

[52] J.Y. Lee, H.S. Ryu, S.S. Yoon, E.H. Kim, S.W. Yoon, Extracellular-to-Intracellular fluid volume ratio as a prognostic factor for survival in patients with metastatic cancer, Integr. Cancer Ther. 18 (2019) 1534735419847285.

[53] O. Chaudhuri, J. Cooper-White, P.A. Janmey, D.J. Mooney, V.B. Shenoy, Effects of extracellular matrix viscoelasticity on cellular behaviour, Nature 584 (7822) (2020) 535–546.

[54] H. Li, G. Flé, M. Bhatt, Z. Qu, S. Ghazavi, L. Yazdani, et al., Viscoelasticity Imaging of Biological Tissues and Single Cells Using Shear Wave Propagation, vol. 9, 2021.

[55] T.C. Mauntel, M.A. Clark, D.A. Padua, Effectiveness of myofascial release therapies on physical performance measurements: a systematic review, Athl. Train. Sports Health Care 6 (4) (2014) 189–196.

[56] N. Anderson, D.G. Robinson, E. Verhagen, K. Fagher, P. Edouard, D. Rojas-Valverde, et al., Under-representation of women is alive and well in sport and exercise medicine: what it looks like and what we can do about it, BMJ Open Sport Exerc Med 9 (2) (2023) e001606.

[57] P. Ritz, S. Vol, G. Berrut, I. Tack, M.J. Arnaud, J. Tichet, Influence of gender and body composition on hydration and body water spaces, Clin. Nutr. 27 (5) (2008) 740–746.