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Acute local and remote responses to foam rolling: An inter-set and contralateral thermographic analysis☆,☆☆,☆☆☆

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ABSTRACT

Background: The aim of this study was to investigate the acute effects of foam rolling (FR) on both local (right hip) and contralateral (left hip) ROM associated with each respective tissue hardness (TH) and skin temperature (TsK) responses both locally (right hamstrings) and contralaterally (left hamstrings).

Methods: Thirty-seven participants completed two conditions: control (CC) and foam rolling (FR; 4 × 30 rolls targeting the right hamstrings). Outcomes included TsK, TH, and ROM, assessed both locally and contralaterally. TsK was measured at baseline and after each FR set, or every 30 s during CC. TH and ROM were evaluated at baseline and post-intervention.

Results: FR significantly increased ROM both locally and contralaterally ($p < 0.001$). In the treated limb, ROM gains were accompanied by a reduction in TH ($p = 0.017$) and a TsK rise emerging only after the fourth FR set ($p = 0.031$). Contralateral ROM improved ($p < 0.001$) without concurrent changes in TH or TsK.

Conclusion: FR elicited a significant acute ROM increase in both treated and contralateral limbs. In the treated limb, a minimum of four sets was required to evoke a measurable thermal response, as indicated by TsK. The local ROM enhancement was also accompanied by a decrease in TH. Conversely, the contralateral ROM gain occurred without alterations in TsK or TH, implying the involvement of alternative mechanisms. These findings suggest that FR may elicit remote effects, offering a potential alternative when direct application is limited by pain or injury. Future studies should clarify the mechanisms driving contralateral ROM enhancements.

1. Introduction

Foam rolling (FR) is a commonly used technique aimed at enhancing joint range of motion (ROM) and is applied in both acute and chronic settings or integrated into warm-up routines (Konrad et al., 2022). The improvements in ROM associated with FR may be attributed to various physiological mechanisms, including increased temperature (warm-up effect), enhanced stretch tolerance, and increased soft-tissue compliance (Adamczyk et al., 2020; Yoshimura et al., 2021b; Nakamura et al., 2023; Konrad et al., 2022). Specifically, FR may also enhance ROM by modifying the viscoelastic properties of the tissue through a thixotropic effect, potentially accompanied by a reduction in tissue hardness (TH) (Kasahara et al., 2024; Thomas et al., 2024).

Scientific literature regarding the effects of FR on temperature variations is heterogeneous, with some studies reporting significant increases in skin temperature measured via thermography, while others observe no meaningful changes (Kerautret et al., 2021; Yenil et al., 2024; Yoshimura et al., 2021a; Konrad et al., 2023), underscoring the

☆ How will my personal data be processed, stored, or disclosed?.
☆☆ To take part in the research, you will need to provide some personal information, such as: *name and surname, sex, and age*.
☆☆☆ During the study, the following technical and organizational measures will be applied to effectively uphold data protection principles and safeguard participants' rights:

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need for a comprehensive interpretation of these results. The heterogeneity of findings also extends to the efficacy of FR as a warm-up method. While some studies recommend FR as part of warm-up routines (Warneke et al., 2023), Warneke et al. challenged the established view on FR as an essential component of warm-up protocols, suggesting that the observed improvements in ROM following FR may result from the general physiological effects of warm-up activities. Specifically, they hypothesized that any intervention capable of increasing core and muscle temperature could be used interchangeably or in combination to induce acute ROM enhancements (Warneke et al., 2023, 2024).

Furthermore, the optimal dose of FR required to induce a measurable warm-up effect also remains variable and inconsistent across studies. Hughes et al. found that the minimum effective dose of massage rolling for muscle appears to be 90 s. However, they highlighted the heterogeneity of existing literature and emphasized the need for further research to establish optimal myofascial rolling protocols for enhancing recovery, ROM, and performance (Hughes and Ramer, 2019). Moreover, Hendricks et al. suggested that the optimal duration of FR for achieving flexibility benefits appears to be between 90 and 120 s (Hendricks et al., 2020). However, the majority of studies primarily focused on ROM and performance outcomes, without providing clear evidence regarding the minimum FR dose required to produce measurable increases in temperature (either muscle, core or TsK) and thus establish a potential warming effect. Therefore, based on these findings, an unexplored

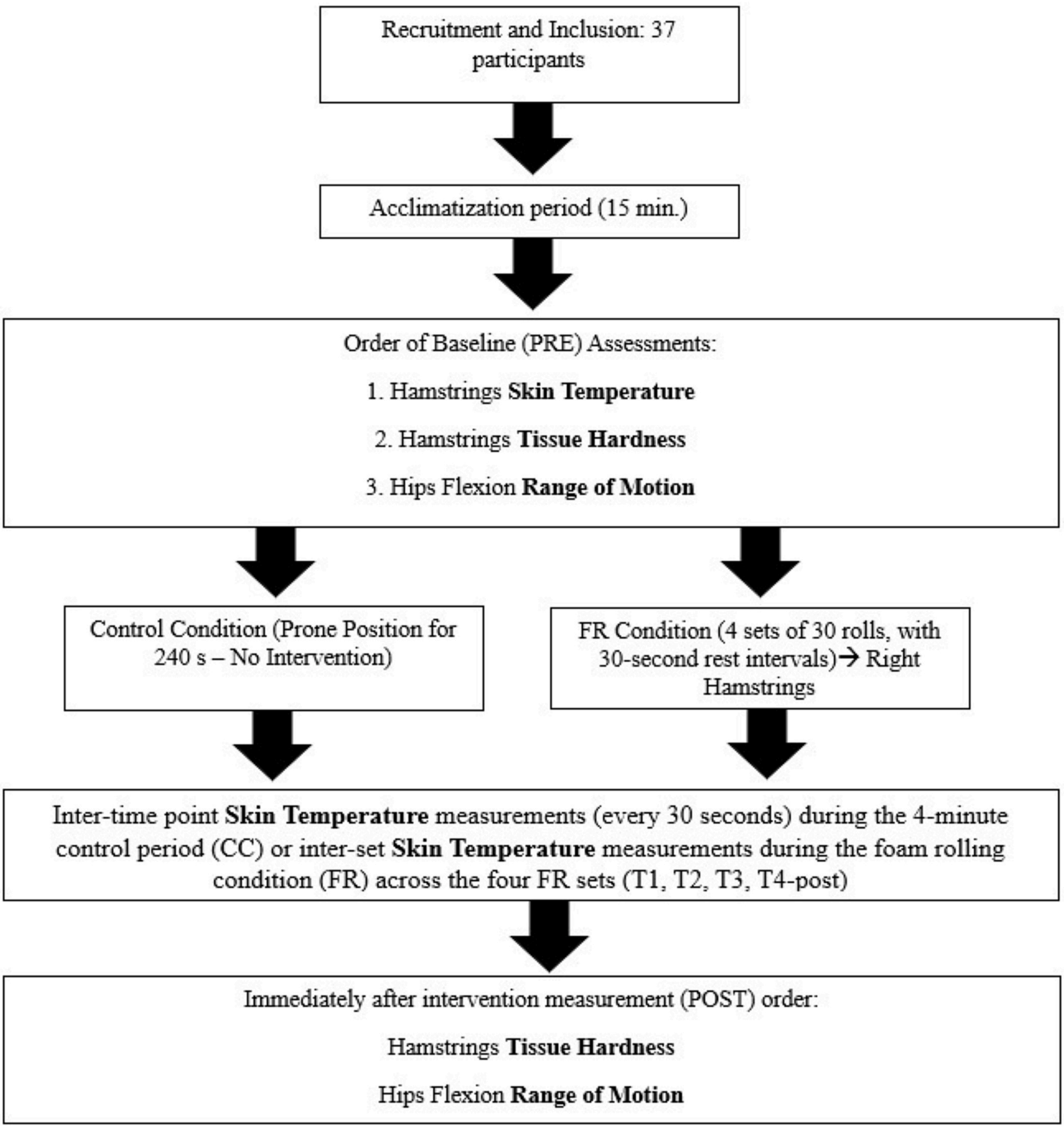

Fig. 1. Study Design Flowchart. Each participant underwent both conditions in a randomized order, with a minimum wash-out period of 48 hours between sessions.

research area is the investigation of TsK trends across multiple FR sets to determine the minimum dose required to produce measurable warming effects. Given the potential relationship between TsK, blood flow, and perfusion (Vuksanovic et al., 2008), along with FR's potential capacity to influence these components (Hotfiel et al., 2017; Schroeder et al., 2021; Schroeter et al., 2023), TsK may offer valuable insights into the heating mechanisms associated with FR.

In addition, as this study also examined changes in TH as a potential mechanism underlying FR-induced variations in ROM, it is important to note that current evidence on alterations in TH and stiffness remains inconsistent. Even from a mechanical standpoint, studies employing elastosonography, tensiomyography, and myotonometry have reported conflicting results regarding stiffness responses to FR (Mayer et al., 2020; Pepper et al., 2021; Schroeder et al., 2021; Szajkowski et al., 2025).

Several studies also investigated the remote FR effects in addition to the local effects (Hendricks et al., 2020; Konrad et al., 2022; Pinto et al., 2025). These most commonly overlooked effects on the contralateral limb's ROM, muscle soreness, pain pressure threshold, and muscle stiffness (Kelly and Beardsley, 2016; Cheatham and Baker, 2017; Kasahara et al., 2022). In this regard, we hypothesized that FR could elicit not only local improvements in ROM, potentially mediated by reductions in TH or localized increases in temperature, but also non-local effects in the contralateral limb, possibly involving a systemic or global warming response (Warneke et al., 2023, 2024). Therefore, this study aims to investigate the acute effects of FR on local but also contralateral ROM associated with each respective TH and TsK in both local and contralateral regions in order to understand any potential moderating variables.

2. Methods

2.1. Participants

A total of 37 participants (22 males: 25.6 ± 4.60 years, 71.1 ± 11.6 kg, 173 ± 7.29 cm; 15 females: 23.7 ± 3.65 years, 58.3 ± 11.2 kg, 160 ± 8.70 cm) took part in the study. Given the crossover design, each participant underwent two conditions (Fig. 1) in a randomized order with at least 48h apart from each session. The a priori sample size estimation was performed using G*Power software (version 3.1.9.7) to determine the number of participants required to achieve adequate statistical power for a repeated-measures ANOVA (within–between interaction). The analysis was conducted with an effect size (f) of 0.25, an α error probability of 0.05, and a power (1–β) of 0.80. The model specified two groups, two repeated measurements, a correlation among repeated measures of 0.5, and a nonsphericity correction (ε) of 1. Based on these parameters, the required total sample size was estimated to be 34 participants (Thomas et al., 2024).

Participants were drawn from the university student population and needed to be free from orthopaedic and neurological diseases. Exclusion criteria included a prior history of lower limb injuries. All participants signed an informed consent form explaining the study protocol, risks, and potential benefits. The bioethical committee of the University of Palermo approved the research (protocol n°170/2023), which complied with the Helsinki Declaration and EU guidelines for clinical research best practices.

2.2. Procedure

All participants attended the laboratory on two separate occasions, spaced at least 48 h apart and scheduled at the same time of day. Each participant underwent two conditions in a randomized order (determined using the randomization tool from www.randomizer.org): Control (CC) and FR.

To account for the potential influence of ROM measurements on subsequent variables, the order of baseline measurements was the following: TsK, TH and subsequently ROM (Fig. 1). For TsK assessments, each participant underwent five measurements: at baseline, and after the first (T1), second (T2), third (T3), and fourth (T4-post) set in the FR condition. In the CC, TsK measurements were collected at baseline and then every 30 s for four additional time points (T1, T2, T3, and T4-post) during the control period, with no intervention applied.

For both right and left hamstrings TH assessments, each participant underwent two measurement sessions: one at baseline (PRE) and another immediately following the FR intervention or control period (POST). Similarly, for hip flexion ROM assessments on both the right and left hips, measurements were conducted at two time points: baseline and immediately after completing either the four FR sets or the control period (POST).

2.3. Outcomes

All measures were collected by the same investigator. For TsK assessments, each participant underwent a single measurement at each time point. TH and ROM measurements were collected three times at each time point, with the mean value used for analysis.

2.4. Skin temperature

Thermal images of the right and left hamstrings were obtained using the FLIR ONE® Edge infrared camera (FLIR Systems), which was connected to an iOS smartphone. The FLIR ONE mobile application for iOS (FLIR ONE v 6.3.1, FLIR Systems, App Store, Apple) was used to operate the camera. Laboratory equipment and the environment were prepared at least 30 min prior to the start of the procedures, and the thermal imaging camera was switched on 10 min before the first measurement. The laboratory temperature was maintained at 24 °C during each visit (Fernández-Cuevas et al., 2015). To acclimate to the controlled environmental temperature (24 °C), participants wore shorts and lay prone on a medical bed for 15 min before the procedures, adhering to the recommended minimum acclimatization period of at least 10 min. This ensured the regions of interest (ROIs) remained exposed and untouched by any surfaces. The infrared camera was positioned using a tripod, ensuring consistent placement and a fixed distance (less than 1 m) from the ROIs, as shorter distances are recommended for imaging fixed body areas (Fernández-Cuevas et al., 2015). During the intervention session (FR), participants slowly adopted a prone position on the medical bed throughout each 30-s rest interval between FR sets. This allowed for the acquisition of thermal images using the infrared camera, which was consistently positioned in the same location on a tripod and angled downward to accurately capture the designated ROIs. After the photo was taken, participants slowly returned to the exercise station to perform the next set. In the CC, participants were instructed to maintain a prone position on the medical bed for a 4-min control period. During this time, four thermal images were captured at 30-s intervals, mirroring the imaging protocol used in the FR condition to ensure consistency in data collection between conditions. During thermal image acquisition with the infrared camera, participants lay prone on the medical bed in a fully relaxed state.

Thermographic images were imported into FLIR Tools (v. 2.10.0, FLIR Systems, Apple App Store) for analysis (Fig. 2). Skin emissivity was set to 0.98, reflecting the emissivity of clean human skin. The average TsK within the defined ROIs, specifically the muscle bellies of the right and left hamstrings, was measured in degrees Celsius (^{O}C).

2.5. Tissue hardness

The TH measurements were conducted using a portable TH meter (NEUTONE TDM-N1; TRY-ALL Corp., Chiba, Japan), designed to assess penetration distance under a standardized pressure of 14.71 N (1.5 kgf). The order of TH measurements of the right and left hamstrings was randomized for each participant. For the evaluation of right and left

Fig. 2. Thermographic image with graphical representation of ROIs for quantitative analysis.

hamstrings TH, the ischiatic tuberosity served as the proximal anatomical reference, while the center of the popliteal fossa was used as the distal reference. TH measurements were obtained by identifying the center of the upper third of the hamstrings muscle belly as the primary measurement site. During the TH assessments, participants were positioned in a prone position on a medical bed and instructed to remain fully relaxed. To enhance measurement reliability, the reference points were precisely marked using a dermal marker prior to data collection. For each site, three consecutive measurements were recorded, and their mean value was calculated and used for statistical analysis.

2.6. Hips flexion ROM

The measurement order of right and left hip ROM was randomized for each participant. For the assessment of right and left hip flexion ROM, participants lay supine, while inelastic straps secured the contralateral leg to prevent compensatory movements. ROM was measured using the active straight leg raise (ASLR) test, with the ankle dorsiflexed and the leg fully extended to evaluate hamstring extensibility (Lim and Park, 2019). Hips flexion ROM (in degrees) was recorded using the GYKO inertial system (Microgate, Bolzano, Italy), placed just above the knee. At each time point, three measurements of right and left hip flexion were recorded, with participants instructed to attain their maximal ROM during each assessment. For analysis, the average of the three recorded measurements was used. To minimize the influence of visual input on perceived sensations, participants were instructed to keep their eyes closed during the tests.

2.7. Intervention

The FR intervention targeted the right hamstrings of each participant and was administered in four 30 roll sets, with 30 s of rest between sets. Participants were instructed to apply a pressure level of at least 8 out of 10 during the intervention. A low-cost, commercially available roller (Bodymate, 30 cm in length, 15 cm in diameter, made of medium-density expanded polypropylene foam with a GRID surface) was used. This type of roller was chosen following the recommendations of prior studies (Cheatham and Stull, 2019). The muscle belly of the hamstrings was positioned over the GRID surface of the roller. Each set required participants to perform 15 rolls in a proximal direction and 15 rolls in a distal direction, covering the entire area between the popliteal region and the ischiatic tuberosity. Each roll in both directions lasted 1 s, resulting in a 30-s duration for each set. Rolling timing was monitored using a metronome app on a mobile device (Metronomo: Tempo lite ver. 5.0.7, App Store, Apple).

2.8. Statistical analysis

Results were presented as means ± standard deviations. A paired *t*-test was conducted to compare baseline measurements between the two conditions (CC and FR). The coefficient of variation (%CV) was reported to assess measurement reliability (Ficarra et al., 2024). To determine differences in the main variables, a repeated-measures analysis of variance (ANOVA) for time and groups was conducted. For TsK, the only outcome analyzed across more than two levels, sphericity was assessed using Mauchly's test. When violated, the Greenhouse–Geisser correction was applied. When a significant time-by-group interaction was observed, post-hoc Scheffé corrections were applied to identify sub-group and time-specific differences. Effect sizes (ES) were calculated for all main analyses using partial eta squared (η^2p) as the ES metric. The magnitude of the ES was classified as follows: 0.01–0.059 for a small effect, 0.06–0.139 for a moderate effect, and ≥0.14 for a large effect (Middlemis Maher et al., 2013). All analyses were performed with Jamovi (The Jamovi Project, 2021). Jamovi (Version 2.3.28.0) [Computer Software]. Retrieved from https://www.jamovi.org. Significance was considered <0.05 for all analyses.

3. Results

3.1. Reliability of the measures

The %CVs for the right and left hamstrings TsK were 2.65 and 2.72, respectively. The %CVs for right and left hamstrings TH were 5.31 and 5.71, respectively. The %CVs for right and left hip flexion ROM were 4.44 and 3.24, respectively.

3.2. Comparison between values at baseline among conditions

The paired *t*-test showed no significant differences in baseline measurements between conditions (CC and FR) for any assessed variable (TsK, TH, and ROM), confirming the absence of baseline discrepancies or carryover effects.

3.3. Comparison of time points for the CC

No significant differences were observed across time points in the CC for TsK, TH and ROM, indicating no time effect on all variables for this condition.

3.4. Local changes

Tables 1 and 2 show the main results for all groups. A significant time × group interaction was observed in the ANOVA for right hip flexion ($p < 0.001$), as well as for right hamstrings TH ($p = 0.014$)

Table 1
Synthesis of TH and ROM results for each condition and body segment.

Analyzed variable	Local changes (right limb)						ANOVA Time x group
	CC (n = 37)			FR (n = 37)			
	PRE	POST	Δpre-post	PRE	POST	Δpre-post	
Hip flexion ROM (°)	92.5 ± 14.7	90.0 ± 14.5	−2.5	91.9 ± 14.3	99.5 ± 13.7*	7.6*	$p < 0.001$; $F = 56.8$; $n^2p = 0.441$
Hamstrings TH (N)	17.9 ± 3.15	18.0 ± 2.97	0.1	17.8 ± 3.19	16.5 ± 3.64*	−1.3*	$p = 0.014$; $F = 6.29$; $n^2p = 0.080$
	Contralateral changes (left limb)						
Hip flexion ROM (°)	92.4 ± 14.9	90.3 ± 14.9	−2.1	90.4 ± 13.0	99.2 ± 14.6*	8.8*	$p < 0.001$; $F = 68.2$; $n^2p = 0.486$
Hamstrings TH (N)	18.2 ± 3.38	18.5 ± 3.02	0.3	18.8 ± 3.03	18.0 ± 3.81	−0.8	$p = 0.033$; $F = 4.70$; $n^2p = 0.061$

Data are presented as means ± SD; CC: Control Condition; FR: Foam Rolling; PRE: Baseline Evaluation; POST: Immediate post-intervention (FR) or post-control period (CC) assessments; ROM: Range of Motion; TH: Tissue Hardness; ANOVA: Analysis of Variance; n^2p: Partial Eta Squared; *: significant difference compared to baseline.

Table 2
Synthesis of TsK results for each condition and body segment.

Local changes (right limb)												
CC (n = 37)						FR (n = 37)						ANOVA Time x group
PRE	T1	T2	T3	T4-POST	Δpre-post	PRE	T1	T2	T3	T4-POST	Δpre-post	
31.3 ± 1.26	31.1 ± 1.14	31.0 ± 1.11	30.8 ± 1.14	30.8 ± 1.35	−0.5	31.3 ± 1.29	31.0 ± 1.06	31.4 ± 1.02	31.9 ± 1.15	32.1 ± 1.03*	0.8*	$p < 0.001$; $F = 24.47$; $n^2p = 0.254$
Contralateral changes (left limb)												
31.2 ± 1.28	31.1 ± 1.18	31.0 ± 1.14	30.9 ± 1.22	30.8 ± 1.37	−0.4	31.3 ± 1.33	31.1 ± 1.13	31.4 ± 1.11	31.6 ± 1.22	31.7 ± 1.17	0.4	$p < 0.001$; $F = 9.38$; $n^2p = 0.115$

Data are presented as means ± SD; TsK: Skin Temperature; PRE: Baseline Evaluation; CC: Control Condition; FR: Foam Rolling; T1/T2/T3/T4-post: TsK assessments at each time point during CC or between sets in FR; ANOVA Analysis of Variance; n^2p: Partial Eta Squared; *: significant difference compared to baseline.

(Table 1) and TsK ($p < 0.001$) (Table 2). In the FR group, Scheffé post-hoc analysis revealed a significant increase in right hip flexion ROM from baseline to post-intervention ($p < 0.001$), accompanied by a significant reduction in TH over the same interval ($p = 0.017$). A significant increase in TsK of the right hamstrings was observed only after the fourth FR set (T4-post) ($p = 0.031$).

3.5. Contralateral changes

A significant time × group interaction was observed in the ANOVA for left hip flexion ($p < 0.001$), as well as for left hamstrings TH ($p = 0.033$) (Table 1) and TsK ($p < 0.001$) (Table 2). In the FR group, Scheffé post hoc analysis indicated a significant increase in left hip flexion ROM from baseline to post-intervention ($p < 0.001$). Although a significant model interaction was observed, post-hoc analyses revealed no significant differences in either TH or TsK across sets when compared to baseline.

4. Discussion

The aim of this study was to investigate the acute effects of FR applied to the right hamstrings on both local (right limb) and contralateral (left limb) ROM to explore potential mechanisms underlying ROM improvements both locally and contralaterally. Additionally, the study examined local and contralateral TH and TsK as potential determinants of ROM variations. Furthermore, the temporal evolution of TsK was analyzed across four sets of FR to determine whether a minimum FR dosage could elicit a measurable increase in TsK.

Our findings highlight a significant improvement in local ROM (right hip flexion) following FR application to the right hamstrings. These results align with the systematic review and multilevel analysis conducted by Wilke et al., which supports the efficacy of FR in inducing acute ROM enhancements (Wilke et al., 2020), as well as with the findings reported by Konrad et al. (2022). Our findings further suggest that the enhancement of local ROM following the FR intervention may be mediated by both reductions in local TH and increases in local TsK, indicating the potential involvement of both mechanical and thermoregulatory mechanisms. Notably, thermal mechanisms could induce mechanical changes through thixotropic effects (Behm and Wilke, 2019), thereby linking temperature-related responses to alterations in tissue viscoelastic properties. Specifically, our findings on the reduction of local TH in response to FR align with previous studies reporting similar effects (Kasahara et al., 2024; Nakamura et al., 2023). Notably, FR may enhance ROM by altering the viscoelastic properties of the tissue through a thixotropic mechanism (Behm and Wilke, 2019; Warneke et al., 2023), which may also contribute to a reduction in TH (Kasahara et al., 2024; Thomas et al., 2024; Behm and Wilke, 2019; Warneke et al., 2023). Supporting this, Thomas et al. observed that FR could induce a localized decrease in extracellular fluid volume, a factor that may influence tissue rigidity and mechanical properties (Thomas et al., 2024, 2025). However, it should be noted that our findings on TH are not uniformly supported by the existing literature. Conflicting evidence has been reported regarding the effects of FR on TH and stiffness, as assessed through myometry, elastosonography, elastography, tensiomyography, and myotonometry. Specifically, Thomas et al. found no significant changes in TH following FR (Thomas et al., 2025), while other studies reported mixed results in tissue and muscle stiffness, potentially influenced by exercise volume, prior FR experience, or the specific region of application (Mayer et al., 2020; Schroeder et al., 2021; Pepper et al., 2021; Reiner et al., 2023; Vatovec et al., 2024; Hendricks et al., 2020; Szajkowski et al., 2025).

Our results also showed a significant increase in local TsK (right hamstrings) compared to baseline, emerging only after the fourth set of FR. Keraútret et al. reported that FR (applied on quadriceps) performed for a total duration of 2 min was the most effective intervention for increasing local TsK in 42 healthy athletes (Keraútret et al., 2021). Based on the explanations provided by Keraútret et al., it is reasonable to hypothesize that FR may have activated thermoreceptors in the dermis (Keraútret et al., 2021; LaMotte and Campbell, 1978; Ring and de Dear, 1991). However, in contrast to our findings of increased local TsK following FR, Yoshimura et al. reported an opposing trend, characterized by a progressive decrease in TsK at each time point in the FR condition (three sets of 1 min each, with 30 s of rest between sets). However, it is important to consider the small sample size of this study (14 participants), which may have limited the generalizability and reliability of the results (Yoshimura et al., 2021b). Another potential explanation for the lack of TsK increase in the study by Yoshimura et al. is that the authors focused on the calf (Yoshimura et al., 2021b), which, compared to larger muscle groups like the hamstrings, exhibits more limited perfusion, thereby reducing the amount of heat that could be directly transported via the bloodstream to the skin of this region (Stoner et al., 1991). Additionally, unlike our findings, Murray et al. (2016) reported that a single 60-s bout of FR applied to the quadriceps did not induce changes in TsK, as measured by thermography, in twelve adolescent male squash players. The discrepancy with our results may be attributable to differences in exercise volume (60 s vs. 120 s), sample size, and participant characteristics compared to those in the present study.

Moreover, supporting our findings, Warneke et al. proposed that global warming mechanisms could contribute to ROM improvements while also acknowledging that such effects may occur independently of FR (Warneke et al., 2023, 2024). This suggests that ROM improvements may be achieved through alternative heating methods beyond FR, while also highlighting that FR itself could effectively enhance ROM through warm-up mechanisms (Lopez-Samanes et al., 2021; Su et al., 2017; Keraütret et al., 2021). Nevertheless, it is important to note that the relationship between muscle temperature and TsK appears to be weak (Jutte et al., 2001; Karlsbad and Kopp, 1991). To gain more precise and relevant insights into muscle warming, it may be advantageous to utilize instruments capable of assessing muscle temperature at greater depths. For example, Yoshida et al. employed a surface-type deep body thermometer to measure muscle temperature changes following a single bout of heat or cold intervention induced by eccentric contraction (Yoshida et al., 2022). Since a key objective of warm-up is to elevate muscle temperature, and given that TsK is highly influenced by external environmental conditions (Jutte et al., 2001) and frictional forces (e.g., those generated by FR) (Keraütret et al., 2021), it may not reliably reflect deep tissue heating. Therefore, assessing intramuscular temperature may provide a more accurate evaluation of the warm-up effects induced by FR. Specifically, while our findings might suggest that this FR protocol could induce a local warming effect, the weak correlation between TsK and intramuscular temperature, likely due to TsK's heightened sensitivity to environmental factors, must be considered (Jutte et al., 2001; Karlsbad and Kopp, 1991). As such, it remains inconclusive whether an increase in TsK reliably reflects a parallel increase in intramuscular temperature. Moreover, the relationship between TsK and core temperature is inherently complex (Xu et al., 2013), being influenced by a range of physical factors, such as tissue thickness and the thermal properties of underlying tissues (e.g., conductivity and heat capacity), as well as physiological variables, including sweat evaporation and regional blood flow (Xu et al., 2013). Consequently, TsK measurements alone could be insufficient to draw definitive conclusions regarding changes in core temperature. Additionally, it remains of interest to determine whether the observed local increase in TsK reflects a true thermogenic response or is primarily attributable to mechanical friction induced by FR on the skin. In this context, future studies comparing foam rolling with a passive rolling intervention using a roller massager could help elucidate this distinction.

Our data also indicate that FR led to an improvement in ROM in the contralateral (unstimulated limb) despite the absence of significant variations in TH and TsK compared to baseline. Our findings regarding the contralateral ROM improvement observed in the left limb are supported by several previous studies. In particular, Kelly et al. reported increased ankle dorsiflexion ROM in the contralateral limb following three 30-s bouts of FR applied to the ipsilateral limb, attributing this effect to enhanced stretch tolerance (Kelly and Beardsley, 2016). Similarly, Killen et al. observed an increase in passive hip flexion ROM in the contralateral limb after applying ten 30-s FR sets to the knee flexors of the dominant limb, also suggesting increased exercise tolerance as a potential underlying mechanism (Killen et al., 2019). Konrad et al., through their scoping review, also observed ROM changes in the contralateral limb following FR interventions. However, they advised caution in interpreting these findings and emphasized the need for further research to confirm and elucidate the underlying mechanisms (Konrad et al., 2023). In the present study, the increased contralateral (left hip flexion) ROM in the absence of changes in TH and TsK of the left hamstrings could suggest the potential involvement of other underlying mechanisms. It is important to note that, although the present study primarily focused on the mechanisms related to temperature and stiffness variations, other factors may also contribute to the observed ROM changes. These may include increases in pain pressure threshold or stretch tolerance (Konrad et al., 2022, 2023; Thomas et al., 2025), as well as the involvement of a single, likely reflexive, centrally mediated mechanism that could explain ROM gains in both limbs, independent of local thermal or mechanical changes. As reported by Wiewelhove et al., a plausible explanation for acute improvements in flexibility is the influence of FR on central pain modulation systems (Wiewelhove et al., 2019). Mechanical pressure applied to soft tissues may activate skin receptors, reducing pain perception, increasing stretch tolerance, and thereby enhancing flexibility (Wiewelhove et al., 2019). Accordingly, the systematic review by Konrad et al. (2023), alongside other original studies (Nakamura et al., 2021; Aboodarda et al., 2015), indicated that increases in contralateral limb ROM following rolling interventions may be mediated by enhanced non-local pain tolerance and central pain-modulatory mechanisms.

4.1. Limitations of the study

This study has some limitations. Firstly, given the weak relationship between TsK and intramuscular temperature (Jutte et al., 2001; Karlsbad and Kopp, 1991), which prevents confirming with certainty that an increase in TsK corresponds to intramuscular heating, the use of a device capable of directly measuring intramuscular temperature could provide clearer insights into the heating mechanisms induced by FR. Additionally, this study did not assess additional underlying mechanisms that may have contributed to the observed improvements in both local and contralateral ROM, such as a potential increase in stretch tolerance. Future research should therefore aim to investigate these additional physiological mechanisms, such as alterations in pain sensitivity, that could underlie ROM enhancements following FR interventions.

5. Conclusions

Foam rolling significantly enhanced range of motion both locally (right hip flexion) and in the contralateral limb (left hip flexion).

In the treated limb, inter-set analysis of local skin temperature revealed a significant increase from baseline only after the fourth foam rolling set, possibly suggesting that a minimum of four sets of 30 foam rolls, with 30-s rest intervals, could be required to elicit a measurable thermal response, assuming skin temperature is used as an indicator of warm-up. Notably, the increase in local range of motion of the treated limb was accompanied by a reduction in local tissue stiffness, suggesting contributions from both mechanical and thermal adaptations, while additional mechanisms, including central pain modulation, cannot be excluded.

In contrast, the contralateral increase in range of motion occurred in the absence of detectable changes in skin temperature or tissue hardness, indicating the possible involvement of centrally mediated or reflexive mechanisms independent of local biomechanical or thermal factors.

These findings suggest that foam rolling applied to a single region may elicit not only local but also remote effects in non-treated areas, which might prove beneficial when direct intervention is limited by pain, injury, or other limitations. While further research is required to draw definitive conclusions, the present evidence provides a valuable basis for future investigations. Further research should aim to assess skin temperature, tissue hardness, and range of motion at multiple time points throughout the foam rolling protocol to determine whether consistent temporal relationships among these variables emerge. Such analyses may help elucidate the underlying physiological mechanisms mediating local and contralateral effects and contribute to defining an optimal threshold for effective warm-up interventions.

Clinical relevance

- Foam rolling the back of one thigh (hamstrings) can also improve flexibility in the opposite, untreated thigh.
- To produce a noticeable warming effect on the treated area, at least four sets of foam rolling may be needed.
- Foam rolling can elicit contralateral improvements in range of motion and represent an effective adjunctive strategy in healthy populations.

CRediT authorship contribution statement

Gianmarco Pinto: Writing – original draft, Data curation, Conceptualization. **Antonino Scardina:** Writing – review & editing, Conceptualization. **Luca Di Bartolo:** Writing – review & editing. **Masatoshi Nakamura:** Writing – review & editing. **Konstantin Warneke:** Writing – review & editing. **Valerio Giustino:** Writing – review & editing. **Marianna Bellafiore:** Writing – review & editing. **Antonino Bianco:** Supervision. **Ewan Thomas:** Supervision, Formal analysis.

Consent to participate

Approved by the bioethical committee of the University of Palermo (protocol n°170/2023) and adhered to the Helsinki Declaration and EU recommendations for good clinical practices.

Informed consent form research participation adults

The undersigned, born on, and residing in ( ) ZIP, street no. , DECLARES:

- to have received the information sheet for participation in the research *"The effects of the Foam Roller on the properties of the lower-limb muscles"*, to have read it, and to have understood the information it contains;
- to have received thorough oral explanations from the research supervisors, to have had the opportunity to ask all questions deemed necessary, and to have received satisfactory answers;
- to have understood that participation in the study is free and voluntary, that withdrawal is possible at any time without providing any explanation, and that taking part in the research does not entail any direct or indirect economic benefit;
- to have received sufficient information regarding the risks and benefits involved in the study, as described in the information sheet.

Consequently, the undersigned:

- consents to participate in the research
- does not consent to participate in the research

Information notice pursuant to Article 13 of EU Regulation 2016/679 adults

This information notice is provided pursuant to Article 13 of EU Regulation 2016/679 (GDPR).

Personal data, sensitive data, and all information concerning you will be used solely for the institutional purposes of the research *"The effects of the Foam Roller on the properties of the lower-limb muscles."*

The data will be collected and processed in compliance with the applicable legislation: EU Regulation 2016/679 (GDPR) on the protection of natural persons with regard to the processing of personal data and the free movement of such data; Legislative Decree 196/2003, the "Personal Data Protection Code," as amended by Legislative Decree 101/2018, "Provisions for the adaptation of national legislation to EU Regulation 2016/679."

The Data Controller is the University of Palermo, represented by the Rector as legal representative, e-mail: rettore@unipa.it, PEC: pec.@cert.unipa.it.

The Data Protection Officer (DPO) of the University of Palermo is Dr. Antonino Pollara, e-mail: dpo@unipa.it, PEC: dpo@cert.unipa.it.

The internal Data Processor in charge of responding to data subjects is the Director of the Department of Psychological, Pedagogical, Exercise and Educational Sciences, Prof. Gioacchino Lavanco, e-mail: Gioacchino Lavanco.

The collection and processing of personal data are carried out in accordance with the principles of lawfulness, fairness, transparency, purpose limitation, storage limitation, data minimization (adequate, relevant, and limited to what is necessary), accuracy, integrity, confidentiality, and accountability, pursuant to Articles 5 and 6 of EU Regulation 2016/679.

As a data subject, you are entitled to the following rights under Articles 15–22 of EU Regulation 2016/679: the right of access to personal data and all related information (Art. 15); the right to rectification of inaccurate personal data or completion of incomplete data (Art. 16); the right to erasure (Art. 17); the right to restriction of processing (Art. 18); the right to data portability (electronic format only); the right to object to the processing of personal data, including profiling (Art. 21); and the right not to be subject to automated decision-making processes, including profiling (Art. 22).

Information notice pursuant to Article 13 of EU Regulation 2016/679 adults

You also have the right to withdraw your consent at any time (Art. 7, paragraph 3). In that case, the data previously collected will still be used unless you explicitly request their destruction (Art. 17). You also have the right to lodge a complaint with a Supervisory Authority (Art. 77).

- *Data will be made public only in aggregated form* (e.g., *averages), which prevents the disclosure of personal information.*

During the collection and storage phases, the data will be entered into electronic spreadsheets and will be retained even after the completion of the current study, to allow comparisons with future studies carried out in our laboratory.

When presenting the study results, it is expected from the outset that the collected data may be used for multiple publications.

Can my data be shared with third parties?

Data cannot be shared with third parties.

Data may be shared with third parties, within the limits allowed by current legislation, exclusively for research purposes and only with the approval of the Bioethics Committee of the University of Palermo.

Am I required to give my consent?

If you choose to participate, you will be asked to sign the consent form for participation and for the processing of the personal data collected during the research. Consent may be withdrawn at any time, without notice, without consequences, and without needing to provide any justification.

Statement of consent personal data processing Adults

Personal data, sensitive data, and all information concerning you will be used solely for the institutional purposes of the research *"The effects* *of the Foam Roller on the properties of the lower-limb muscles."*

In particular, the collection and processing of personal data, according to the procedures described in the attached information sheet, are carried out in compliance with the principles of lawfulness, fairness, transparency, purpose limitation, storage limitation, data minimization (adequate, relevant, and limited to what is necessary), accuracy, integrity, confidentiality, and accountability, pursuant to Articles 5 and 6 of EU Regulation 2016/679.As a data subject, you are entitled to the following rights under Articles 15–22 of EU Regulation 2016/679: the right of access to personal data and all related information (Art. 15); the right to rectification of inaccurate personal data or completion of incomplete data (Art. 16); the right to erasure (Art. 17); the right to restriction of processing (Art. 18); the right to data portability (electronic format only); the right to object to the processing of personal data, including profiling (Art. 21); the right not to be subject to automated decision-making processes, including profiling (Art. 22).

You also have the right to withdraw your consent at any time (Art. 7, paragraph 3). In that case, the data previously collected will still be used unless you explicitly request their destruction (Art. 17). You also have the right to lodge a complaint with a Supervisory Authority (Art. 77).

Requests must be addressed to the internal Data Processor, the Director of the Department of Psychological, Pedagogical, Exercise and Educational Sciences, Prof. Gioacchino Lavanco, e-mail: gioacchino.lavanco@unipa.it.

In light of the above and the information provided to me:

The undersigned, born in on, and residing in ( ) ZIP, street no. ,

- consents to the processing of their personal data.
- does not consent to the processing of their personal data.

Availability of data

Full data coded of the included studies can be shared upon reasonable request from the corresponding author.

Consent for publication

Not applicable.

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Declaration of competing interest

The authors declare no conflicts of interest.

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