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Delayed Foam Rolling Outperforms Immediate Application: Mechanistic Synergy With Post-Exercise Repair Phases Reduces DOMS and Restores Muscle Function

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KEYWORDS

Foam Rolling,
Delayed-Onset Muscle Soreness,
Muscle Recovery,
Mechanical Stress,
Neuromuscular Function.

ABSTRACT

A randomized controlled trial was conducted with 66 male track and field jumpers to evaluate the effects of immediate and delayed foam rolling (FR) on muscle recovery. Participants performed a standardized exercise protocol and were divided into three groups: immediate FR post-exercise, delayed FR 15 hours post-exercise, and a no-intervention control group. Recovery was measured through vertical jump power and pressure pain threshold (PPT) to assess delayed-onset muscle soreness (DOMS). While both FR protocols significantly reduced DOMS compared to the control, only the delayed FR group showed meaningful improvements in jump power recovery. Delayed FR appears more effective due to its timing, allowing initial inflammation and repair processes to occur before intervention, which enhances tissue remodeling and waste clearance. These results suggest that delayed FR (≥15 hours post-exercise) is a more effective recovery strategy for athletes.

1. Introduction

Foam rolling (FR) training, a form of self-myofascial release (SMR) technique, is currently one of the most popular SMR methods due to its large rolling area and standardized operational procedures.(Michalak et al. 2024) Although existing studies have demonstrated that FR may enhance flexibility, facilitate muscle recovery, improve athletic performance, and reduce delayed onset muscle soreness (DOMS), the results remain inconclusive due to heterogeneity in research methods.(Cheatham et al. 2015) Emerging evidence suggests that the immediate post-exercise period (0–12 hours) coincides with a pro-inflammatory peak phase, during which mechanical loading may exacerbate exercise-induced microtrauma. In contrast, the subsequent repair phase (12–24 hours post-exercise) is characterized by heightened fibroblast activity, where controlled interventions such as foam rolling (FR) can leverage shear forces to facilitate organized collagen realignment and tissue remodeling.(Friden and Lieber 1992, Hendricks et al. 2020, Aune et al. 2019) Concurrently, emerging evidence supports the efficacy of immediate post-exercise FR. Acute FR application reduces arterial stiff-

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Table 1 | Participant Characteristics

Group	Age (years)	Height (cm)	Weight (kg)
Experimental Group 1(E1)	22.5±1.5	180±5	75±5
Experimental Group 2(E2)	23±1.8	178±4.5	73±4.8
Control Group(C)	22.8±1.6	179±4.7	74±4.9

ness and elevates nitric oxide bioavailability, transiently enhancing range of motion (ROM).(Pearcey et al. 2015) Mechanistically, mechanical pressure activates mechanotransduction pathways that drive transcriptional upregulation of COX7B and ND1, accelerating muscle repair,(Crane et al. 2012) while concurrently enhancing lymphatic clearance of metabolic byproducts (e.g., lactate, myoglobin) to mitigate inflammation.(Baechle and Earle 2008) Notably, acute FR intervention correlates with diminished expression of stress markers (e.g., heat shock proteins) and proinflammatory cytokines,(Crane et al. 2012) alongside elevated neutrophil mobilization and attenuated plasma creatine kinase levels,(Smith et al. 1994) collectively suggesting optimized tissue recovery with reduced secondary damage.

In this study, we conducted experiments to investigate: (i) the effects of immediate versus delayed (15 hours post-exercise) FR on athletic performance recovery; and (ii) the impact of immediate versus delayed FR on the occurrence of DOMS. We hypothesized that: (i) there would be no significant differences between the two FR timing protocols regarding athletic performance recovery; and (ii) all participants would experience DOMS post-exercise, but the decline in PPT would be less pronounced in the FR groups.

2. Methods

2.1. Sample Size Justification

A priori power analysis was performed using G*Power 3.1 (Heinrich-Heine-Universität Düsseldorf, Germany) to determine the minimum sample size required for detecting medium-effect differences among groups. Based on a one-way ANOVA design (three groups: immediate FR, delayed FR, control) with an assumed effect size of ($f = 0.25$) (Cohen's convention for medium effects), $\alpha = 0.05$ (two-tailed), and power = 0.80, the analysis yielded a total sample size of 66 participants (22 per group). To account for potential attrition (estimated at 10%), the target enrollment was adjusted to 73 participants. This calculation aligns with prior studies investigating foam rolling interventions and DOMS recovery, ensuring robust detection of clinically meaningful differences in neuromuscular function and pain thresholds.Shanghai Normal University Academic Ethics and Ethics Committee approved the study.

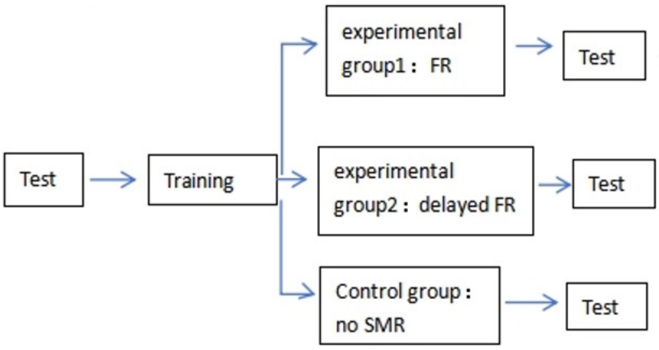

Figure 1 | Flowchart

2.2. Participants

Sixty-six male track and field athletes specializing in jumping events, with over two years of training experience, participated in the study（Table 1）. Participants were randomly assigned to Experimental Group 1 (immediate FR), Experimental Group 2 (delayed FR), or the control group (no FR), with eight participants in each group. All participants volunteered for the study, had no acute joint or muscle injuries in the past six months, and had at least two years of resistance training experience.

2.3. Design

The study included two experimental groups and a control group. All participants were familiarized with the experimental procedures prior to the study (Figure 1). Experimental Group 1 performed FR immediately after the exercise protocol, Experimental Group 2 performed FR 15 hours post-exercise (at 8:00 AM the next day), and the control group did not perform

Figure 2 I Exercise Protocol (from top to bottom: half squat, high pull from knee level, pogo jump;From left to right, the start and end poses)

any form of SMR. Testing was conducted at 2:00 PM the day after the exercise protocol.

2.4. Exercise Protocol

Participants received instruction on the exercise protocol one week in advance and were required to execute it accurately. The training included traditional resistance exercises to simulate the daily training of track and field athletes (Figure 2):

Barbell half squats (70%–80% 1RM; repetitions: 8, 6, 5),High pulls from knee level (70%–80% 1RM; repetitions: 8, 6, 5).

Functional strength exercises:4 sets of 12 consecutive pogo jumps,4 sets of 20 seconds of high-knee running in place.

One-repetition maximum (1RM) was defined as the maximum weight lifted with proper form in a squat to parallel position, with incremental load increases. Participants' 1RM values were tested in advance to calculate individual training loads with precision.

2.5. Foam Rolling Protocol

Both experimental groups followed the same FR protocol(Peacock et al. 2014, Behara and Jacobson 2017, Aune et al. 2019) using a conventional high-density foam roller (length 30 cm, diameter 15 cm; BLACKROLL, Bottighofen, Switzerland).

The FR protocol was performed as shown in Figure 3, following the sequence from A to E: This includes 2 minutes per side for the gluteus maximus

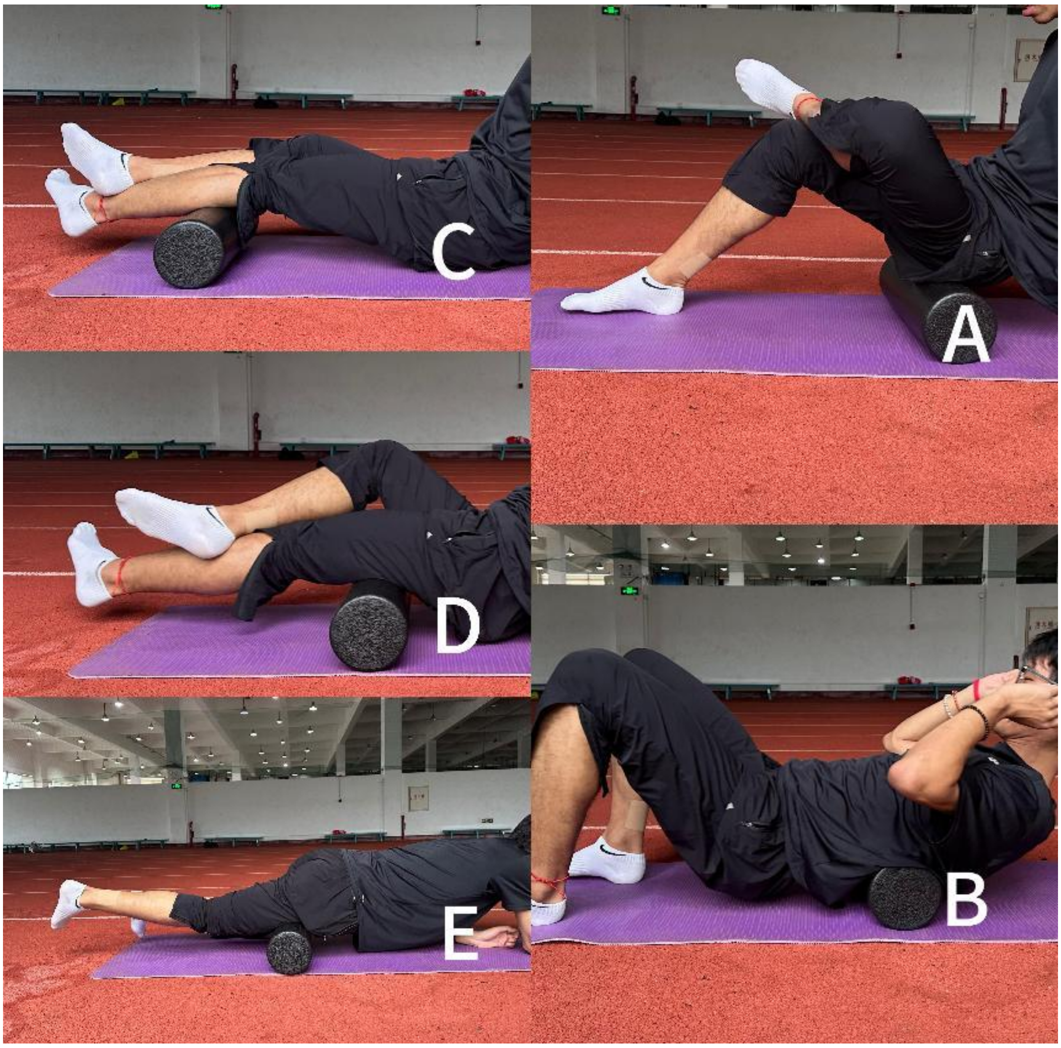

Figure 3 | Foam Rolling Protocol Diagram

and gluteus medius in the hip region, 1.5 minutes for the latissimus dorsi and lower back, 2 minutes per leg for the gastrocnemius and soleus in the calf, 2 minutes per leg for the semitendinosus, semimembranosus, and biceps femoris in the posterior thigh, and 2 minutes per leg for the rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius in the anterior thigh.

3. Equipment and Variables

3.1. Testing Overview

Each testing session comprises the following assessments to comprehensively evaluate the subjects' muscular function and pain perception.

3.2. Muscle Strength

Lower limb muscle power was estimated using the formula proposed by Sayers et al. (Sayers et al. 1999):

$\text{Power(W)}=[\text{Vertical Jump Height(cm)}60.7]+[\text{Body Mass(kg)}\times 45.3]-2055$；

Participants were weighed using the same electronic scale (Delixi, Zhejiang, China), and jump height was measured using the My Jump 2 application, which has been validated for high reliability and validity.(Bogataj et al. 2020, Chow, Kong, and Pun 2023, Haynes et al. 2019) The jump test was adapted from Vaisman et al.(Vaisman et al. 2017) Participants began from a half-squat position with knees flexed at 90°,maintained the position for 2 seconds to minimize the influence of the stretch-shortening cycle (SSC). They then performed a maximal vertical jump. Each participant performed three non-consecutive trials, (Booher et al. 1993)with the highest jump height recorded.

3.3. Pressure Pain Threshold (PPT)

The pressure pain threshold is assessed using a hand-held dolorimeter with a 1 cm rubber tip (Al-

Table 2 | Test Results for PPT and Power

	PPT(kPa)			POWER(W)		
	Pre	Post	Mean Comparison	Pre	Post	Mean Comparison
E1	601.88±13.34	577.50±14.72	P＜0.01	5210.66±143.24	5068.18±181.84	P=0.2156
E2	603.13±12.58	588.13±12.58	P＜0.01	5149.25±101.84	5193.29±96.08	P＜0.01
C	605.00±10.00	548.75±7.98	P＜0.01	5203.89±171.95	5024.43±172.39	P＜0.01

gometer II，Somedic SenseLab，Sweden). This device applies controlled and gradually increasing pressure to specific muscle sites. We put the device on the rectus femoris muscle at 50% of the distance between the anterior spina iliaca superior and the superior part of the patellain the rate of 30kPa/s until the participant reports the sensation of pressure turning into pain.(Baumgart et al. 2019)The data is referred to as Pressure Pain Threshold (PPT), currently defined as "the minimum necessary intensity of a pressure stimulus that is perceived as painful."(Ylinen 2007)Before testing, participants are asked to sit on a chair with their legs naturally bent and feet flat on the ground to ensure the rectus femoris is in a relaxed state.

4. Data Processing

For data analysis, Hedges' g is utilized to evaluate the effects of foam rolling (FR) interventions at different time points on performance and muscle pain between two groups. The calculation of Hedges' g is as follows:

$$g = c_p \frac{\left(M_{\text{post, foam rolling}} - M_{\text{pre, foam rolling}}\right)\left(M_{\text{post, control}} - M_{\text{pre, control}}\right)}{SD_{\text{pre}}}$$

In this context, c_p is a bias correction factor used for small sample sizes,(Morris 2008)aimed at minimizing the bias that may arise from small sample measurements. $M_{post,foamrolling} - M_{pre,foamrolling}$ represents the difference between the post-test and pre-test means for the foam rolling group, while $M_{post,control} - M_{pre,control}$ represents the difference between the post-test and pre-test means for the control group. SD_{pre} denotes the pooled standard deviation of the pre-test measurements.

5. Result

The results of the experimental tests are shown in Table 2 and Figure 4-5.Independent sample t-tests for each group (E1 vs E2; E1 vs C; E2 vs C) revealed no significant differences (t=0.409, p=0.6888; t=0.069, p=0.946; t= -0.3272, p=0.7483), followed by paired sample t-test for the difference between the two data except E1 (P <0.01). To compare the magnitude of the differences, the Hedges' g value analysis was performed, and the results are shown in Table 3.

6. Discussion

Post-exercise stretching and relaxation are essential for recovery,(Medicine 2013)and SMR is an effective method for promoting recovery in most cases .(Casanova et al. 2018) Regarding the timing of post-exercise stretching, many individuals, including athletes, are accustomed to performing it immediately after exercise (immediate recovery), while others prefer to schedule muscle relaxation training for the next morning or on a separate day (delayed recovery).

Table 3 | Hedges' g Effect Sizes for PPT and Power

	PPT	POWER
E1 vs C	2.355	0.159
E2 vs C	3.305	1.337

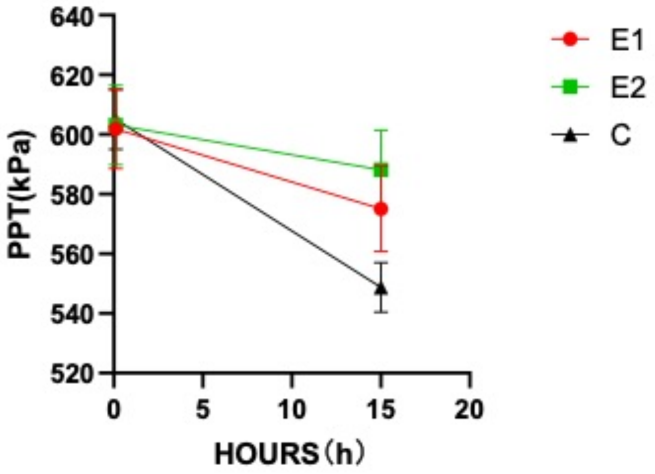

Figure 4

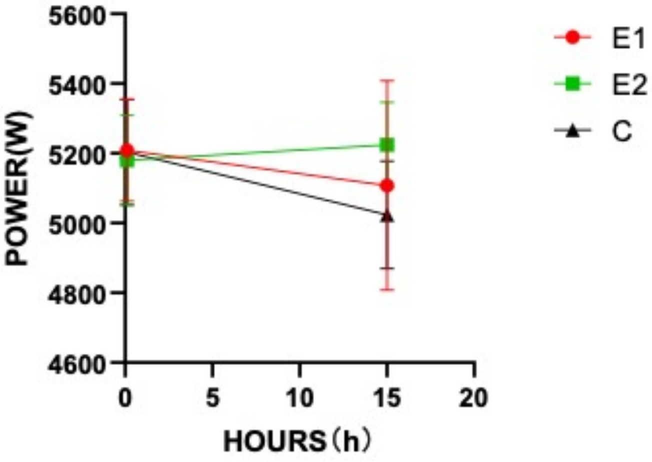

Figure 5

6.1. Pressure Pain Threshold (PPT)

All groups exhibited a significant decrease in PPT post-exercise,indicating the presence of exercise-induced muscle soreness (Figure 4). However, the reduction in PPT was less pronounced in both the E1 and E2 groups compared to the Control group. This suggests that foam rolling effectively mitigated DOMS. Notably, the E2 group demonstrated the smallest decrease in PPT, with a Hedges' g effect size of 3.305, indicating a large effect. This finding implies that delayed foam rolling is more effective in alleviating muscle soreness than immediate foam rolling.

This finding aligns with current international research.(Pearcey et al. 2015, Cheatham et al. 2015, D'Amico and Gillis 2019, Hendricks et al. 2020, Nazarudin et al. 2021)

Furthermore, Experimental Group 2 (delayed FR) exhibited a larger effect size compared to Experimental Group 1 (immediate FR). This may be because delayed FR better facilitates muscle recovery. Post-exercise, muscles experience micro-damage and inflammatory responses.(Friden and Lieber 1992) Immediate FR might increase mechanical stress on the muscles, potentially hindering the initial repair process. Delaying FR by 15 hours allows for initial self-repair, after which FR can enhance blood circulation, reduce the accumulation of inflammatory mediators, expedite the removal of metabolic waste, and more effectively alleviate muscle pain and promote strength recovery.

6.2. Jump Power

In terms of muscle strength recovery, both Experimental Group 2 and the control group showed significant reductions in jump power. Interestingly, Experimental Group 1 did not show a significant change in jump power ($p = 0.216$). An examination of the mean values and standard deviations suggests that this may be due to outliers within the group (e.g., one participant's post-test jump power increased by approximately 395 W compared to the pre-test, while others remained stable or slightly decreased). The Hedges' g results for jump power also indicated a large effect size for delayed FR, whereas immediate FR did not show a significant effect. This contrasts with the PPT effect sizes and suggests that delayed FR may have advantages over immediate FR in terms of strength recovery.

The scatter plots in Figure 4 and Figure 5 support these results. In Figure 4, the Control group's PPT values decreased substantially post-exercise, whereas the E1 and E2 groups exhibited smaller reductions, with the E2 group's post-test PPT values remaining closer to pre-test levels. In Figure 5, the Control group's jump power decreased notably post-exercise; the E1 group showed minimal change, and the E2 group participants either maintained or improved their jump power in the post-test.

7. Conclusion

Comparative analysis indicates comparable efficacy between immediate and delayed FR interventions in attenuating exercise-induced myalgia. However, delayed FR protocols demonstrated superior performance in restoring neuromuscular function and mitigating symptoms of DOMS. Practical implementation considerations suggest preferential application of delayed FR regimens, particularly within self-administered recovery contexts. Post-exercise fatigue states associated with high-intensity training may compromise subject adherence and technique precision in self-administered FR interventions when implemented immediately following physical exertion. Furthermore, acute mechanical loading through FR modalities on fatigued musculature may transiently amplify tissue stress biomarkers, potentially counteracting early-phase regenerative pathways.

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