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Acute effects of foam rolling versus passive rest following a single bout of explosive squat jump exercise

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Coşkun Rodoplu, Josef Fischer, Christian Burger, Mert Arabacı, Esra Kurt, Hüseyin Topçu, Ufuk Şekir, Ramiz Arabacı & Andreas Konrad

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Title

Acute Effects of Foam Rolling vs. Passive Rest Following a Single Bout of Explosive Squat Jump Exercise

Head title

Muscle Activation and foam rolling

Author information

Coşkun Rodoplu[1,2], Josef Fischer[2], Christian Burger[2], Mert Arabacı[1,3], Esra Kurt[3], Hüseyin Topçu[3], Ufuk Şekir[4], Ramiz Arabacı[3], Andreas Konrad[2]

[1] Department of Common Courses, Bursa Technical University, Bursa, Turkey

[2] Institute of Human Movement Science, Sport and Health, Graz University, Graz, Austria

[3] Department of Physical Education and Sports Teaching, Bursa Uludağ University, Bursa, Turkey

[4] Department of Sport Medicine, Bursa Uludağ University, Bursa, Turkey

Coşkun Rodoplu: coskun.rodoplu@btu.edu.tr, https://orcid.org/0000-0003-0613-9006

***Josef Fischer:** josef.fischer@uni-graz.at, https://orcid.org/0009-0004-0678-9169

Christian Burger: christian.burger@uni-graz.at, https://orcid.org/0009-0008-5594-4291

Mert Arabacı: mertarabaci2002@hotmail.com, https://orcid.org/0009-0004-4122-3400

Esra Kurt: esrakrt87@gmail.com, https://orcid.org/0000-0003-3947-0360

Hüseyin Topçu: huseyintopcu@uludag.edu.tr, https://orcid.org/0000-0003-0623-883X

Ufuk Şekir: ufuksek@uludag.edu.tr, https://orcid.org/0000-0003-2735-8697

Ramiz Arabacı: ramizar@uludag.edu.tr, https://orcid.org/0000-0001-8403-5742

Andreas Konrad: andreas.konrad@uni-graz.at, https://orcid.org/0000-0002-5588-1824

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*: Corresponding Author

Josef Fischer, Institute of Human Movement Science, Sport and Health

University of Graz, Mozartgasse 14, A-8010 Graz, Austria

Tel: +43(0)316380-8327, Email: josef.fischer@uni-graz.at

Abstract

A single session of explosive resistance exercise can induce acute neuromuscular fatigue, highlighting the need for effective recovery strategies. Foam rolling (FR) is commonly used to facilitate neuromuscular and functional restoration. This study examined whether FR, compared with passive recovery (PR), differentially affects post-exercise balance, jump performance, and lower-limb neuromuscular excitation assessed via surface electromyography. Twenty-one physically active men (age 21.8 ± 1.6 years; height 180.7 ± 8.0 cm; weight 75.1 ± 10.8 kg) completed both FR and PR in a randomized crossover design. Assessments were conducted prior to exercise (pre-test), immediately post-exercise (mid-test), and following the recovery interventions (post-test). All participants performed the squat jump protocol (5 sets × 6 reps at 30% 1RM and 6–8 reps at body weight), followed by performance tests (dynamic balance, static balance, horizontal and vertical jumping) and muscle activity assessment. For physical tests, significant intervention × time interactions were observed for posteromedial and composite scores of dynamic balance, static balance, and horizontal jumping ($p = .002–.024$; $\eta_p^2 = .171–.262$), indicating greater improvements following FR compared with PR, whereas no significant interactions were observed for anterior and posterolateral dynamic balance or vertical jumping. Muscle excitation showed significant main effects of time across all measures ($p \leq .001–.032$; $\eta_p^2 = .158–.598$), with intervention × time interactions limited to a subset of muscles ($p = .011–.035$; $\eta_p^2 = .154–.201$). FR may help preserve static and dynamic balance, as well as horizontal jump performance, following a single bout of explosive resistance exercise; however, its effects on vertical jump and muscle excitation appear limited. Future research should incorporate broader neuromuscular assessments and varied FR protocols across diverse populations to clarify underlying mechanisms and optimize recovery.

Keywords: acute recovery, muscle activation, balance performance, jump performance

1. Introduction

Explosive movements of the lower extremities, such as jumping, require the production of force at high velocity within a short time frame, thereby imposing high mechanical and neuromuscular demands on the involved musculature [1]. The squat jump is an explosive exercise performed from a

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static starting position with the knee and hip joints in flexion and requires rapid concentric muscle action. Such explosive exercise applications can induce substantial neuromuscular stress in the lower-extremity muscles depending on the applied load, number of repetitions, and movement execution, which may lead to performance alterations associated with acute fatigue [2]. Indeed, the literature reports transient reductions in jump performance, force production, and balance parameters following fatigue-inducing jump exercises [3-5]. In this context, there is a need to examine performance and neuromuscular responses to single session, high-intensity explosive exercise while considering post-exercise recovery strategies.

Common post-exercise recovery modalities include passive rest (PR), stretching, hydrotherapy and massage [6, 7]. More recently, foam rolling (FR) has gained popularity because of its ease of application, low cost and suitability for field use. Proposed mechanisms of FR include alterations in soft-tissue viscoelastic properties, increased local blood flow, modulation of nociceptive input, and reorganization of mechanoreceptive/proprioceptive afferent signalling. Through these pathways, FR may influence movement quality at both mechanical and neurophysiological levels compared with passive rest [8]. The majority of the literature has examined FR under non-fatiguing conditions and reported variable effects of a single FR session on different performance outcomes [9, 10]. In contrast, evidence regarding the potential of FR to limit performance decrements or accelerate recovery in the context of exercise-induced fatigue remains limited and heterogeneous [11-13]. While some studies have reported improvements in balance and jump performance following a single FR session after fatiguing exercise [14-16], others have demonstrated trivial or non-significant effects on these parameters [17-19].

In the literature, the relationship between lower-limb performance and neuromuscular responses following jump-based exercise has not been clearly established [20]. In particular, studies simultaneously examining the effects of FR on muscle function and surface electromyography (sEMG) responses

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after intense exercise are scarce. Within the limited available evidence, some studies have reported that FR improves jump performance, balance and muscle activation during these tasks [11, 21, 22], whereas others have failed to demonstrate any meaningful additional benefit [23]. These inconsistencies may be related to the methodological challenges associated with interpreting sEMG signals during complex tasks such as balance and jumping. Given that pre-activation and eccentric contraction phases are particularly critical for analysis [24, 25], there is a clear need for studies that evaluate the neuromuscular effects of FR using synchronized performance tests and sEMG measurements following fatiguing exercise.

To our knowledge, no study has concurrently examined a fatiguing explosive exercise session (i.e., squat jumps) followed by FR on balance, jump performance and sEMG responses. Therefore, the aim of the present study was to investigate the acute effects of FR, compared with PR, on single-leg stance test, Y-Balance test, single-leg hop for distance, vertical jumping performance and on sEMG activity following a single session of explosive exercise. It was hypothesized that FR, relative to PR, would preserve or modestly enhance acute physical performance and would facilitate faster normalization of sEMG-assessed muscle excitation, particularly in the quadriceps, hamstrings and calf muscles.

2. Materials and Methods

2.1. Participants

An a priori sample size calculation using G*Power 3.1.9.7 Software (Düsseldorf, Germany) for a repeated-measures ANOVA (within-between interaction) based on countermovement jump performance data from Heinke et al. [26], ($\alpha = 0.05$, $\beta = 0.95$, $f = 0.40$), indicated that a minimum of 18 participants was required for a crossover study design. Therefore, a total of 21 healthy male participants (age: 21.8 ± 1.6 years; height: 180.7 ± 8.0 cm; weight: 75.1 ± 10.8) were recruited. Inclusion criteria were regular engagement in moderate-intensity physical activity at least three days per week and eligibility for exercise participation according to the Physical

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Activity Readiness Questionnaire for Everyone (PAR-Q+), while exclusion criteria included the presence of any neurological or muscular disorder, use of stimulant substances, use of medications that could influence physical performance prior to testing, and a history of any musculoskeletal injury affecting performance within the previous three months.

2.2. Study Design

This study employed a randomized crossover design. Participants attended the laboratory on three separate occasions separated by at least one week, and the order of the FR or PR conditions was randomized using an online randomization program (www.randomizer.org). Participants completed both conditions in a counterbalanced order. A one-week washout period was implemented to minimize potential carryover effects. However, carryover or order effects were not formally evaluated.

At the first session (familiarization), participants provided their self-reported height, while body mass and body composition were assessed using a bioelectrical impedance analyzer (Tanita BC-418MA, Tokyo, Japan). A 10RM test was performed to estimate individual 1RM values, and participants were familiarized with all performance tests, the exercise protocol, and the FR procedure. In the second and third sessions, participants completed a standardized warm-up, maximum voluntary isometric contraction (MVIC) measurements for sEMG normalization, pre-test, exercise protocol, mid-test, recovery interventions, and post-test. The exercise protocol consisted of 5 sets of 6–8 repetitions performed under loaded (30% 1RM) and unloaded conditions. Exercise intensity was monitored using the Borg Rating of Perceived Exertion (RPE) scale. All physical performance assessments were performed at pre-test, mid-test, and post-test time points, while muscle excitation was simultaneously recorded using a sEMG system (Ultium EMG, Noraxon USA Inc., Scottsdale, AZ, USA).

Participants were instructed to refrain from strenuous exercise for 48 h prior to each session. All sessions were conducted at the same time of day under controlled laboratory conditions (20–22°C). The study was conducted

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in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Bursa Uludağ University (Date: 16/01/2023; No: 2023-1/41; ID: 2011-KAEK-26/45). The study design is illustrated in Figure 1.

Figure 1. Design of the study.

2.3. Procedures

2.3.1. Tests

Single-leg stance test: This test was used to assess participants' static balance and was administered as a single-leg balance task on the dominant (kicking) limb; participants stood barefoot on the dominant leg with their hands on their hips and the time from attainment of a stable posture until the first loss of postural stability (e.g., marked sway, movement of the supporting foot, or contact of the lifted foot with the ground) was recorded using a handheld stopwatch, with timing verified through synchronized video recordings obtained from the EMG acquisition system; the test was performed three times on the dominant leg with eyes closed and the mean value was used for analysis [27].

Y-Balance test: This test was used to assess dynamic lower-limb balance and functional performance. Participants stood barefoot on the dominant leg with their hands on their hips and were instructed to reach as far as possible with the contralateral limb in the anterior, posteromedial and posterolateral directions. During each trial, the stance foot was kept fixed and balance and controlled movement were maintained. Reach distances were measured using a tape fixed to the floor. Each direction was tested three times, and the mean reach distance (cm) was recorded. The Y-Balance test composite reach distance was calculated by dividing the sum of the mean reach distances in the three directions by leg length and multiplying by 100. All data were normalised to leg length for statistical analysis [28].

Single-leg hop for distance: This test assessed horizontal single-leg jump performance. Participants stood barefoot at a marked starting line with their hands on their hips and were instructed to jump forward as far as possible on the dominant leg while maintaining balance upon landing. Jump distance was

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measured using a tape fixed to the floor. Each leg was tested three times, and the mean value (cm) was used for analysis. All data were normalised to leg length [29].

Countermovement jump: Vertical jump performance was measured using a Sport Expert™ MPS-501 device (Tümer Elektronik LTD., Turkey) with a precision of 0.1 cm. Jump height was calculated based on flight time. Participants performed maximal vertical jumps from a self-selected semi-squat start position (approximately 90° knee flexion) without a preparatory arm swing, keeping their hands on their hips, and completed three trials with 15 s rest between attempts, with the mean jump height (cm) used for analysis.

2.3.2 Borg Rating of Perceived Exertion (RPE; 6–20)

Following the squat jump exercise protocol, perceived exertion was assessed using the Borg RPE scale, which ranges from 6 (no exertion) to 20 (maximal exertion), and is a well-established instrument with demonstrated validity and reliability [30]. Participants verbally reported their overall exertion immediately after completion of the exercise protocol, and mean values were used for subsequent analyses.

2.3.3. Estimation of One-Repetition Maximum (1RM)

During the familiarization session, following a 10-minute general warm-up, participants performed a 10RM test using a guided Smith machine during a standardized half-squat exercise corresponding to approximately 90° of knee flexion, in line with established methodological recommendations. The depth of the half-squat was carefully controlled using a manual goniometer and an adjustable tripod bar, and participants were instructed to descend until their hips lightly contacted the bar to ensure movement consistency. Based on observations obtained during the warm-up phase and participant feedback, a load approximating the individual 10RM was selected, and participants performed repetitions until momentary muscular failure. The repetition tempo was standardized using a metronome at four seconds per repetition (two seconds eccentric and two seconds concentric). One-

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repetition maximum (1RM) values were subsequently estimated using the Brzycki equation [31].

2.3.4. Exercise Procedure

The exercise protocol involved the sequential performance of loaded (with dumbbells; 30% of 1RM) and unloaded (body weight only) conditions. All exercises were performed with maximal intended velocity and an explosive intent. The protocol comprised 5 sets of 6 repetitions in the loaded condition, whereas a range of 6–8 repetitions was applied in the unloaded condition to account for inter-individual differences related to fatigue. The total duration of the protocol was approximately 15 minutes. To mitigate the potential negative effects of fatigue on exercise performance and injury risk, a 2-min inter-set rest interval was provided [32]. The exercise protocol is detailed in Table 1.

Table 1. The details of exercise.

2.3.5. Recovery

The recovery protocol was implemented under two conditions: PR and FR. In the PR condition, participants remained seated on a chair for 8 minutes without movement. In the FR condition, participants performed rhythmic rolling movements over the hamstrings, quadriceps and gastrocnemius muscles using a foam roller (Blackroll, Bottighofen, Switzerland); the intervention was initiated on the dominant limb and subsequently repeated on the non-dominant limb in the same sequence. Each muscle group was rolled for 30 seconds, performed in two sets (total 60 seconds), with one complete rolling cycle (from distal to proximal and back) every 2 seconds. During hamstring and quadriceps rolling, participants were instructed to maintain a perceived pressure intensity of 7 out of 10 on a visual analogue scale (VAS-10), a widely used and validated instrument for the assessment of subjective pressure and pain intensity [33]. When perceived pressure dropped below this level, additional downward pressure was applied by the investigator. For the gastrocnemius muscles, rolling was performed using body weight only, without additional external pressure. The total rolling time

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for all muscle groups on both legs was approximately 6 minutes, when including transitions and electrode placements for the post-test, the overall duration of the intervention was about 8 minutes. The FR intervention is illustrated in Figure 2.

Figure 2. FR intervention protocols. (The red arrows in the figure illustrate the rhythmic back-and-forth motion of the foam roller, moving from the lower (distal) to the upper (proximal) part of the thigh and back again. This description refers to images (A) and (B), while image (C) shows three rolling regions that include the rectus femoris, vastus medialis and vastus lateralis muscles. The red circles indicate the rolling movement along the muscle, highlighting the specific areas targeted during foam rolling.)

2.3.6. Surface Electromyography and Data Processing

Muscle activity was recorded from the dominant leg using a portable 16-channel surface electromyography system (Ultium EMG, Noraxon USA Inc., Scottsdale, AZ). Differential bipolar surface electrodes (Ag/AgCl) were placed parallel to the muscle fibers on the quadriceps muscles (rectus femoris, vastus medialis, vastus lateralis), the hamstring muscles (biceps femoris, semitendinosus), and the medial gastrocnemius. Electrode placement followed the SENIAM guidelines and anatomical references for innervation zones with an interelectrode distance of approximately 20 mm [34]. To minimize skin impedance, the electrode sites were shaved, cleaned with alcohol, and verified through a contraction test prior to placement.

MVIC measurements for normalization were obtained as follows: for the quadriceps, participants performed maximal knee extension against a dynamometer in a seated position with the knee at 60° flexion; for the hamstrings, maximal knee flexion was performed against manual resistance in a prone position with the knee at 30° flexion; and for the gastrocnemius, participants performed a heel raise while standing and lightly touching a table with two fingers for balance [35, 36]. Verbal encouragement was provided to ensure maximal effort, and three trials were conducted before each session. The mean of the highest 3-second root mean square (RMS) values was used as the reference MVIC [37]. For all tests, the mean RMS values obtained from three trials for each muscle were normalized to these MVIC values and expressed as %MVIC.

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Electromyography signals were recorded during all tests from the quadriceps, hamstrings, and gastrocnemius muscles. RMS values were calculated for predefined task-specific phases: the balance maintenance period during the static balance test, the 2-s reaching (eccentric) phase during the dynamic balance test, and the push-off phase during the vertical and horizontal jumping tasks. For the dynamic balance, the reaching phase was defined as the interval from the onset of single-leg stance to maximal reach, whereas for the horizontal and vertical jump the push-off phase was defined as the period from maximal knee flexion to take-off. Phase identification was performed using the synchronized video recording integrated within the electromyography system [38].

Electromyography signals were recorded at 2000 Hz using myoResearch 4.0 software (Noraxon USA Inc., Scottsdale, AZ, USA). A band-pass filter of 10–500 Hz was applied to the recordings, and the RMS values of the signals were smoothed using a 150 ms moving average window. Video recordings were analyzed in slow motion to identify push-off and take-off phases, and the corresponding signals were extracted. The processed data were exported to Microsoft Excel (Microsoft Corp., Redmond, WA, USA) and normalized to each muscle's MVIC. All normalized data were subsequently transferred to IBM SPSS Statistics 27.0 software (IBM Corp., Armonk, NY, USA) for further statistical analysis.

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2.4. Statistical Analyses

Descriptive statistics are presented as mean and standard deviation. The Shapiro-Wilk test confirmed that all data were normally distributed. A two-way repeated measures ANOVA was conducted to compare time and group interactions [two interventions (FR, PR) × three time points (pre-test, mid-test, post-test)] for physical performance and muscle excitation outcomes, followed by pairwise comparisons. Mauchly's test of sphericity was conducted for all repeated-measures outcomes. Among the physical performance outcomes, a violation of sphericity was observed only for the single-leg stance test. Among the muscle excitation outcomes, violations were

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observed for the single-leg stance test (vastus medialis and vastus lateralis), posterolateral direction (gastrocnemius), and countermovement jump test (rectus femoris and vastus medialis). Greenhouse–Geisser corrections were applied for these variables, whereas sphericity was assumed for all other outcomes. Effect sizes were calculated as partial eta square (η_p^2) for ANOVA [39], with values above 0.01, 0.06, and 0.14 indicating "small", "medium", and "large" effect sizes, respectively. Bonferroni correction was applied for all the post-hoc tests. The magnitude of significant pairwise differences was evaluated using Cohen's *d* effect size ($d = t/\sqrt{n}$) and interpreted using standard thresholds: trivial <0.20, small 0.20–0.59, moderate 0.60–1.19, large 1.20–1.99, and very large ≥ 2.0 [40]. The significance level was set as $p < 0.05$.

3. Results

The anthropometrics of the participants are presented in Table 2. The mean ± SD values of all tests performed at the three different time points (pre-test, mid-test, and post-test), as well as the results of the ANOVA and significant pairwise comparisons, are presented in Table 3, Figure 3, and S2 File while the sEMG activity of the all muscles during these tests is shown in Figure 4, S1, S3 File. The Borg scores immediately after exercise were 18.5 ± 0.8 for the FR group and 18.7 ± 0.7 for the PR group, with no significant difference between conditions ($p > 0.05$). In addition, from pre-test to mid-test, significant time effects were observed for most physical performance outcomes (Y-Balance anterior reach, composite scores, countermovement jump and single-leg hop distance test; all $p < .05$; see table 3), confirming exercise-induced fatigue in both groups.

Table 2. Descriptive statistics of the participants

Table 3. Physical Performance Outcomes of Participants: Means, Confidence Intervals, and ANOVA Analysis

Figure 3. Mean ± SD physical performance outcomes for the FR and PR groups at pre-test, mid-test, and post-test time points. Panels show: (a) anterior reach, (b) posteromedial reach, (c) posterolateral reach, and (d) composite score of the Y-Balance test; (e) single-leg stance test performance, (f) single-leg hop distance normalized

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to leg length, and (g) countermovement jump height (cm). (* = $p < 0.05$, significantly different from mid-test; # = significantly different from post-test).

Figure 4. Mean ± SD sEMG activity of all muscles for the FR and PR groups at pre-test, mid-test, and post-test time points. Panels show sEMG activity during the reaching phase of the Y-Balance test in the (A) anterior, (B) posteromedial, and (C) posterolateral directions; (D) throughout the stance phase of the single-leg stance test; (E) during the propulsion phase of the single-leg hop distance test normalized to leg length; and (F) during the propulsion phase of the countermovement jump. Significant within-group pairwise comparisons from post-hoc tests are indicated by symbols (* = $p < 0.05$, significantly different from mid-test; # = significantly different from post-test).

With respect to physical performance outcomes, significant main effects of time with large effect sizes were observed for the Y-Balance test composite score, posteromedial direction, static balance, and horizontal jump (see Table 3). No significant intervention × time interactions were found for the Y-Balance test anterior and posterolateral direction, or vertical jump, suggesting similar responses between FR and PR for these outcomes. In pairwise comparisons, significant time effects were observed, with effect sizes predominantly in the moderate range and occasional small and large effects (see Figure 3 and S2 File).

Regarding the sEMG outcomes, significant main effects of time with moderate to large effect sizes were observed for the Y-Balance test anterior (rectus femoris, vastus medialis, biceps femoris), posteromedial (all muscles), posterolateral (rectus femoris, vastus medialis, vastus lateralis, biceps femoris and semitendinosus), static balance (biceps femoris and semitendinosus), horizontal jump (rectus femoris, vastus medialis, gastrocnemius), and vertical jump (vastus lateralis). In addition, significant intervention × time interactions with large effect sizes were identified for the Y-Balance test anterior (vastus medialis), posteromedial (vastus lateralis), posterolateral (biceps femoris), static balance (biceps femoris and semitendinosus), and horizontal jump. No significant intervention × time interactions effects were observed for vertical jump performance (see S1 File). In pairwise comparisons, significant time effects with predominantly moderate-to-large effect sizes were observed (see S1, S3 File and Figure 4).

4. Discussion

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In this study, we compared the acute effects of FR and PR following a single bout of explosive squat jump exercise on dynamic balance, static balance, horizontal and vertical jump performances, as well as sEMG activities of the various contributing muscles. The main findings indicate that, compared with PR, FR significantly enhanced dynamic balance, static balance, and horizontal jump performance following the fatiguing explosive squat jump exercise, whereas no meaningful effect of FR was observed on vertical jump performance. Another important finding is that, although FR induced time-specific increases and decreases in muscle excitation at certain time points, the overall effect on sEMG excitation was limited and no consistent excitation pattern was evident across muscles or tests. Importantly, pre-test to mid-test comparisons demonstrated significant declines in most physical performance outcomes across both groups, confirming that the explosive squat jump protocol successfully induced acute fatigue prior to the recovery interventions.

Y-Balance test performance improved significantly following FR compared with PR, yet no consistent or significant changes in sEMG were observed. This pattern indicates that normalized MVIC-derived surface EMG amplitude did not increase and that the observed performance gains cannot be straightforwardly attributed to elevated muscle excitation [41, 42]. Rather, FR's may have been related to changes in soft-tissue viscoelasticity (e.g., thixotropic phenomena), enhanced proprioceptive feedback, or the contribution of muscles not monitored in the present protocol. In particular, gluteal muscles, rectus abdominis, erector spinae and soleus can meaningfully support balance and stabilization during the Y-Balance test, and their omission may partially obscure sEMG–performance relationships [43, 44]. Consistent with Borisavljević et al. [42], short-duration FR (30 s) may produce transient increases in sEMG whereas longer applications (60 s) tend to attenuate excitation while preserving maximal output, a pattern that could be compatible with equivalent force at lower excitation levels and thus improved neuromuscular efficiency. Consequently, the FR-related

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improvement in Y-Balance test may reflect a combination of unmeasured muscular contributions, refined intermuscular coordination and tissue-level changes rather than a simple increase in monitored muscle excitation. Future studies should incorporate broader sEMG sampling and complementary kinematic/structural measures to clarify these mechanisms.

With respect to static balance, performance improved significantly following FR compared with PR. sEMG analyses indicated that these improvements were not accompanied by widespread alterations in lower-limb excitation, with meaningful changes largely confined to the hamstring muscles (e.g., biceps femoris and semitendinosus). This finding aligns with previous evidence suggesting that, during single-leg stance, postural control is predominantly regulated by the gastrocnemius muscles rather than the hamstrings [25] and is consistent with the results of the present study (see Figure 4). Consequently, the observed enhancement in static balance is unlikely to be primarily driven by increased muscle excitation. Instead, it may reflect FR-induced improvements in proprioceptive feedback, which have been shown to facilitate static balance performance [15, 45]. In addition, reductions in muscle stiffness and concomitant increases in flexibility may optimise muscle tone, thereby facilitating motor control and postural stability [18, 46, 47]. The absence of significant differences in excitation between FR and PR further supports the notion that FR does not directly augment neural drive but may instead attenuate exercise-induced pain or inflammation, thereby limiting neural inhibition and preserving neuromuscular function [11, 41]. Collectively, these mechanisms may offer a plausible explanation for the FR-related improvements in static balance performance observed in the present study, independent of marked changes in sEMG excitation.

Regarding SLHD performance, FR produced an acute improvement while no consistent or significant changes in sEMG excitation were observed. The literature that concurrently examines acute FR effects on horizontal explosive tasks with sEMG is limited. Cavanaugh et al. [48] reported that quadriceps FR reduced antagonist biceps femoris muscle excitation during single-leg

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hurdle jumps, whereas hamstring FR did not affect quadriceps muscle excitation, suggesting that this reduction may reflect reciprocal inhibition mediated by increased pain perception. Similarly, our previous study [49] showed that FR may improve balance and horizontal performance without producing significant sEMG changes. Although the evidence is sparse, the collective data are consistent with the hypothesis that FR enhances SLHD primarily via improvements in muscle–tendon viscoelasticity and movement efficiency rather than by increasing neuromuscular excitation; greater flexibility may preferentially benefit horizontal hopping tasks [50, 51]. In sum, acute FR effects appear to be associated more with tissue-level properties, motor control and intermuscular coordination than to direct increases in sEMG-measured excitation. Future acute studies should combine broader sEMG sampling with kinematic, kinetic and tissue-property measures to elucidate the underlying mechanisms.

The countermovement jumps findings indicate that FR did not produce a meaningful acute effect on vertical jump height or on sEMG excitation during the task when compared with PR. This is a result that accords with prior reports of inconsistent FR effects on power and explosive performance [52, 53], as well as with our previous study [18]. Conceptually, this is plausible: exercise-induced reductions in force may reflect both central (e.g., reduced neural drive) and peripheral (e.g., impaired excitation-contraction coupling, metabolite accumulation, myofibrillar disruption) mechanisms, which brief FR interventions are unlikely to immediately reverse. The absence of significant changes in muscle excitation during the vertical jump, particularly during the push-off phase, is consistent with previous biomechanical and sEMG evidence [54, 55], and suggests that short-term FR primarily induces sensory or local tissue–related effects rather than modulating motor unit behaviour or enhancing performance in high-velocity stretch–shortening cycle (SSC) tasks.

Notably, whereas FR improved single-leg hop for distance test performance in the present study, no countermovement jump benefit was

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observed and neither test showed consistent excitation changes. This dissociation likely reflects fundamental biomechanical differences between the tasks. The countermovement jump is a bilateral, vertical, high-velocity SSC movement that places greater demand on the anterior kinetic chain (e.g., rectus femoris, vastus medialis, vastus lateralis), whereas the single-leg hop for distance test is a single-leg, forward horizontal push-off with longer/slower SSC characteristics and proportionally greater posterior-chain (e.g., biceps femoris) involvement [53, 55]. Our muscle-specific excitation patterns are consistent with this distinction (see Figure 4). Taken together, the data suggest that acute FR effects on performance may be linked to enhanced proprioceptive sensitivity, improved dynamic balance control, or modified muscle–tendon mechanical properties (e.g., stiffness/flexibility) than by direct increases in neuromuscular excitation.

From a practical perspective, the present findings indicate that FR should be considered a complementary recovery strategy rather than a primary intervention. The observed effects were task-specific and generally modest; however, improvements in balance and horizontal jump performance may still be relevant in the immediate recovery period following a single bout of fatigue-inducing explosive exercise. Therefore, FR may be integrated into post-exercise routines as an adjunct method to support short-term functional performance, rather than being viewed as a standalone approach capable of producing broad or uniform performance enhancements.

This study has several limitations. First, the inclusion of male participants only limits the generalizability of the findings. Future studies should include female participants, particularly when examining muscle excitation outcomes. Second, the sEMG recordings during balance and jump tests did not include additional lower-limb muscles (e.g., soleus, tibialis anterior, and gluteal muscles), which may have restricted a more comprehensive evaluation of excitation patterns; future research should incorporate these muscle groups. Moreover, the absence of force-platform data (e.g., center-of-pressure measures) limited detailed analyses of postural control strategies,

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and the inclusion of such measurements would be valuable in future studies. In addition, muscle–tendon stiffness was not assessed; integrating this parameter could provide further insight into potential mechanical adaptations. Finally, future investigations should examine different FR durations and intensities and compare FR with other recovery modalities to better elucidate its effectiveness.

5. Conclusion

In conclusion, following a single bout of explosive squat jump exercise, FR acutely enhanced static and dynamic balance (e.g., single-leg stance, Y-Balance test) and horizontal jump performance (e.g., single-leg hop for distance), whereas effects on vertical jump performance (e.g., countermovement jump) and muscle excitation were modest. These improvements may reflect indirect mechanisms such as enhanced proprioceptive input and altered muscle–tendon viscoelastic properties, rather than direct changes in neuromuscular excitation. From a practical perspective, FR may serve as an effective and accessible strategy to acutely improve balance and horizontal jump performance, while additional or complementary interventions may be needed to enhance vertical jump outcomes. Future research employing more comprehensive sEMG configurations, center-of-pressure analyses, and varied FR protocols across diverse populations is warranted to clarify mechanisms and optimize performance outcomes.

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Statements and Declarations

i. Data availability statement

The data analyzed during the current study are accessible from the corresponding author on reasonable request.

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ii. Authors' contributions

CR, JF, UŞ, RA, and AK contributed to study design. CR, MA, and HT contributed to data collection. CR, JF, CB, MA, HT, EK, UŞ, RA, and AK drafted the manuscript, and all authors made critical revisions to the manuscript. All authors approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

iii. Funding statement/acknowledgements

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Table 1. Details of the exercise protocol.

Set	SJ with load (30% of 1RM)	Rest Interval (~sec)	SJ with no load (bodyweight only)	Rest (min)	Duration (~min)
1	SJ x 6 reps	10-15	SJ x 6-8 reps	2	3
2	SJ x 6 reps	10-15	SJ x 6-8 reps	2	3
3	SJ x 6 reps	10-15	SJ x 6-8 reps	2	3
4	SJ x 6 reps	10-15	SJ x 6-8 reps	2	3
5	SJ x 6 reps	10-15	SJ x 6-8 reps	2	3
Total	30 reps	~50-75 sec	30-40 reps	10 min	~15 min

Note: SJ: Squat Jump; reps: repetitions; 1RM = 1 repetition maximal effort.

iv. Conflict of interest disclosure

The authors declare no competing interests.

Table 2. Descriptive statistics of the participants

Variable	Mean (SD)	Min	Max
Age (years)	21.8 (1.6)	20.0	26.0
Height (cm)	180.7 (8.0)	165.0	200.0
Weight (kg)	75.1 (10.8)	57.4	101.2
BMI (kg/m^2)	22.9 (2.3)	19.2	27.2
FAT (%)	8.4 (5.0)	2.8	18.7
FM (kg)	6.7 (4.8)	1.8	16.7
FFM (kg)	68.4 (7.5)	55.5	84.5
TBW (kg)	50.1 (5.5)	40.6	61.9
Load (30% of 1RM)	29.2 (7.7)	18.0	50.0
PAL (MET-min/wk.)	1170.6 (878.7)	330.0	4200.0

Note: BMI: body mass index; FAT: total body fat; FM: fat mass; FFM: fat free mass; TBW: total body water; RM: repetition maximum; PAL: physical activity level.

v. Ethics approval statement and consent to participate

The Ethics Committee of the Bursa Uludağ University provided ethical approval for the study (Date: 16/01/2023; No: 2023-1/41; ID: 2011-KAEK-26/45). Written informed consent was obtained from all participants prior to their participation in the study.

Abbreviations

ANOVA: Analysis of variance
FR: Foam rolling,
MVIC: Maximum voluntary isometric contraction,
PR: Passive recovery,
RM: Repetition maximum,
RMS: Root mean square,
sEMG: Surface electromyography.

Tables

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Table 3. Physical Performance Outcomes of Participants: Means, Confidence Intervals, and ANOVA Analysis

Variable	Time	FR		PR		Intervention X Time			Time		
		Mean (SD)	[95% CI]	Mean (SD)	[95% CI]	F (2,40)	*p*	η_p^2	F (2, 40)	*p*	η_p^2
Y-Balance test *(%)* *Anterior*	Pre-test	78.32 (4.49) †	(76.28 – 80.36)	77.63 (4.70) †	(75.49 – 79.77)	.164	.850	.008	8.703	**<.001***	.303
	Mid-test	76.02 (6.31)	(73.15 – 78.90)	75.60 (5.24)	(73.21 – 77.98)						
	Post-test	77.58 (4.15)	(75.69 – 79.47)	76.51 (4.56)	(74.43 – 78.59)						
Posteromedial	Pre-test	106.52 (6.94) §	(103.36 – 109.69)	107.40 (5.70)	(104.81 – 110.00)	7.074	**.002***	.261	6.066	**.005***	.233
	Mid-test	104.24 (9.32) §	(100.00 – 108.48)	103.68 (7.37)	(100.32 – 107.03)						
	Post-test	109.70 (8.02)	(106.04 – 113.35)	104.91 (7.73)	(101.40 – 108.43)						
Posterolateral	Pre-test	102.30 (8.78) §	(98.30 – 106.30)	102.96 (7.47)	(99.56 – 106.36)	2.160	.129	.097	3.742	**.032***	.158
	Mid-test	101.00 (10.82) §	(96.07 – 105.93)	99.37 (7.93)	(95.76 – 102.98)						
	Post-test	104.49 (8.44)	(100.65 – 108.33)	101.30 (8.95)	(97.23 – 105.37)						
Composite	Pre-test	95.70 (5.41) §	(93.24 – 98.17)	95.99 (4.83) †	(93.79 – 98.19)	4.121	**.024***	.171	7.975	**.001***	.285
	Mid-test	93.74 (7.88) §	(90.15 – 97.32)	92.90 (5.60)	(90.36 – 95.45)						
	Post-test	97.26 (5.98)	(94.54 – 99.98)	94.23 (5.57)	(91.70 – 96.77)						
Single-leg stance test *(sec)*	Pre-test	33.04 (17.57) §	(25.04 – 41.04)	34.04 (19.49)	(25.17 – 42.91)	5.124	**.013***	.204	8.192	**.004***	.291
	Mid-test	28.08 (18.33) §	(19.73 – 36.42)	29.86 (20.30)	(20.62 – 39.10)						
	Post-test	42.64 (17.42)	(34.71 – 50.57)	31.38 (16.63)	(23.81 – 38.95)						
	Pre-test	154.20 (19.27) §	(145.43 – 162.97)	152.50 (22.11) †	(142.44 – 162.57)	6.454	**.004***	.244	15.796	**<.001***	.441

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Single-leg hop for distance *(%)*	Mid-test	146.86 (22.66) §	(136.54 – 157.17)	141.00 (22.75)	(130.65 – 151.36)						
	Post-test	163.57 (18.17)	(155.30 – 171.84)	147.66 (16.31)	(140.24 – 155.09)						
Countermovement jump *(cm)*	Pre-test	36.15 (8.07) †	(32.48 – 39.82)	35.37 (6.08) †§	(32.60 – 38.13)	.208	.813	.010	19.623	**<.001***	.495
	Mid-test	32.35 (7.28) §	(29.04 – 35.66)	31.40 (6.64)	(28.38 – 34.42)						
	Post-test	34.29 (6.74)	(31.22 – 37.36)	32.95 (6.12)	(30.17 – 35.74)						

FR: foam rolling group; PR: passive recovery group; †: significantly different from the mid-test ($p < 0.05$); §: significantly different from the post-test ($p < .05$); η_p^2: partial eta square; *: statistically significant difference ($p < .05$).

Figures

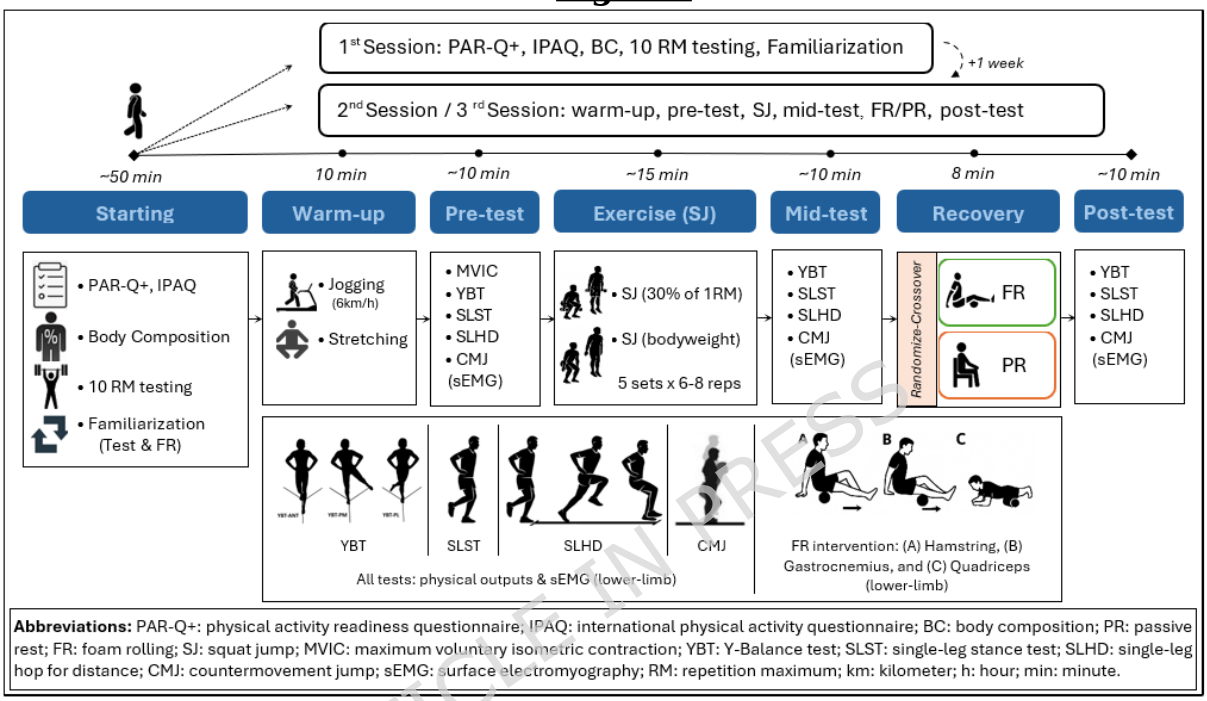


Figure 1. Design of the study.

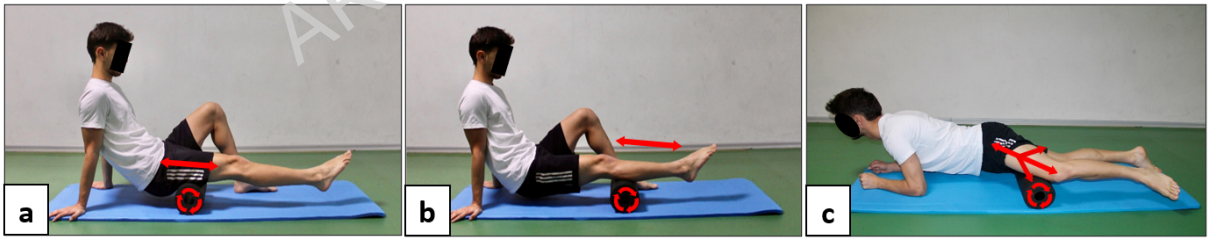


Figure 2. FR intervention protocols. (Red arrows indicate the rhythmic, bidirectional foam-rolling movement along the thigh from distal to proximal and back, shown in panels (a) and (b). Panel (c) shows the three rolling regions targeting the rectus femoris, vastus medialis, and vastus lateralis muscles, with red circles marking the roller path along each muscle belly.)

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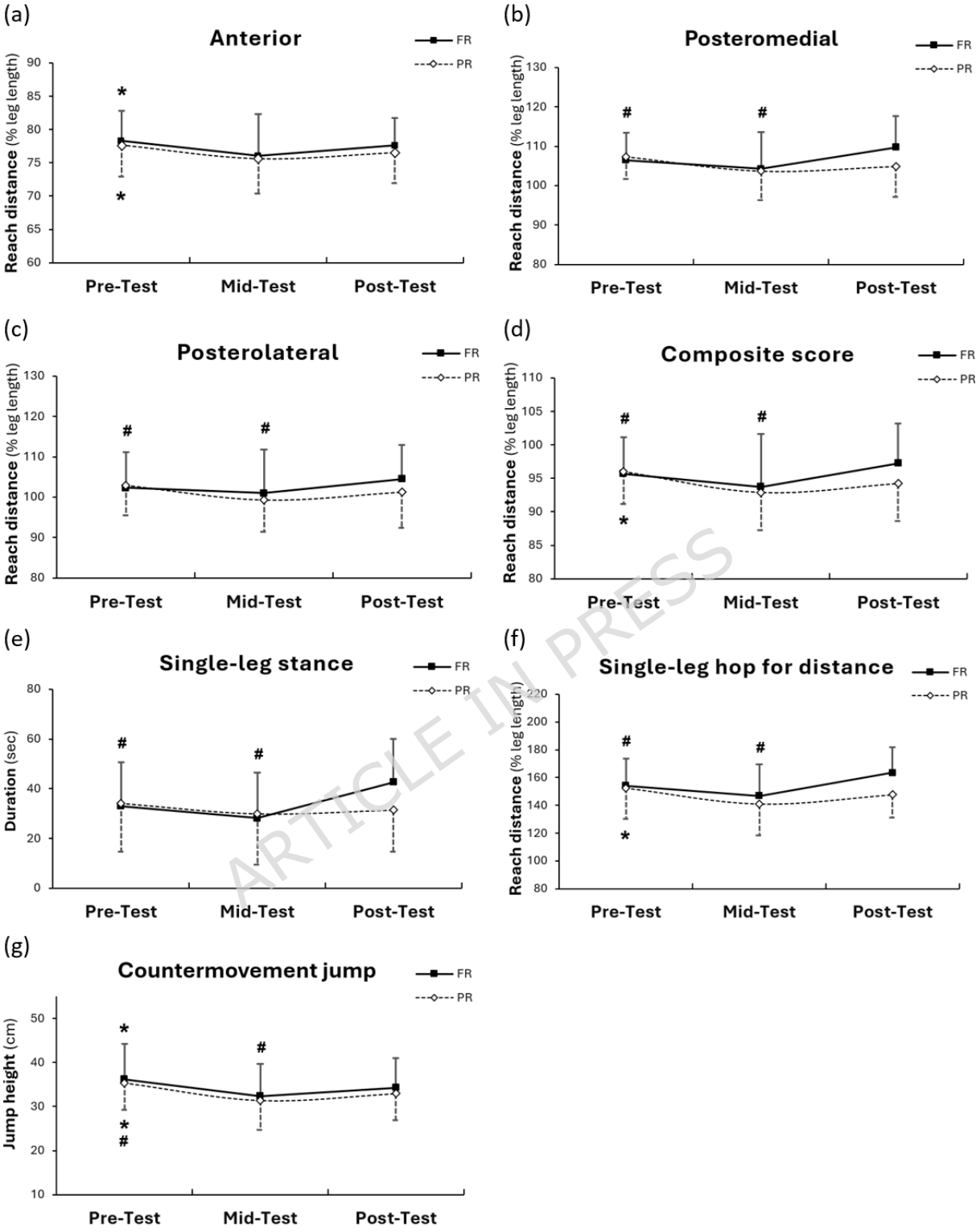


Figure 3. Mean ± SD physical performance outcomes for the FR and PR groups at pre-test, mid-test, and post-test time points. Panels show: (a) anterior reach, (b) posteromedial reach, (c) posterolateral reach, and (d) composite score of the Y-Balance test; (e) single-leg stance test performance, (f) single-leg hop distance normalized

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to leg length, and (g) countermovement jump height (cm). (* = $p < 0.05$, significantly different from mid-test; # = significantly different from post-test).

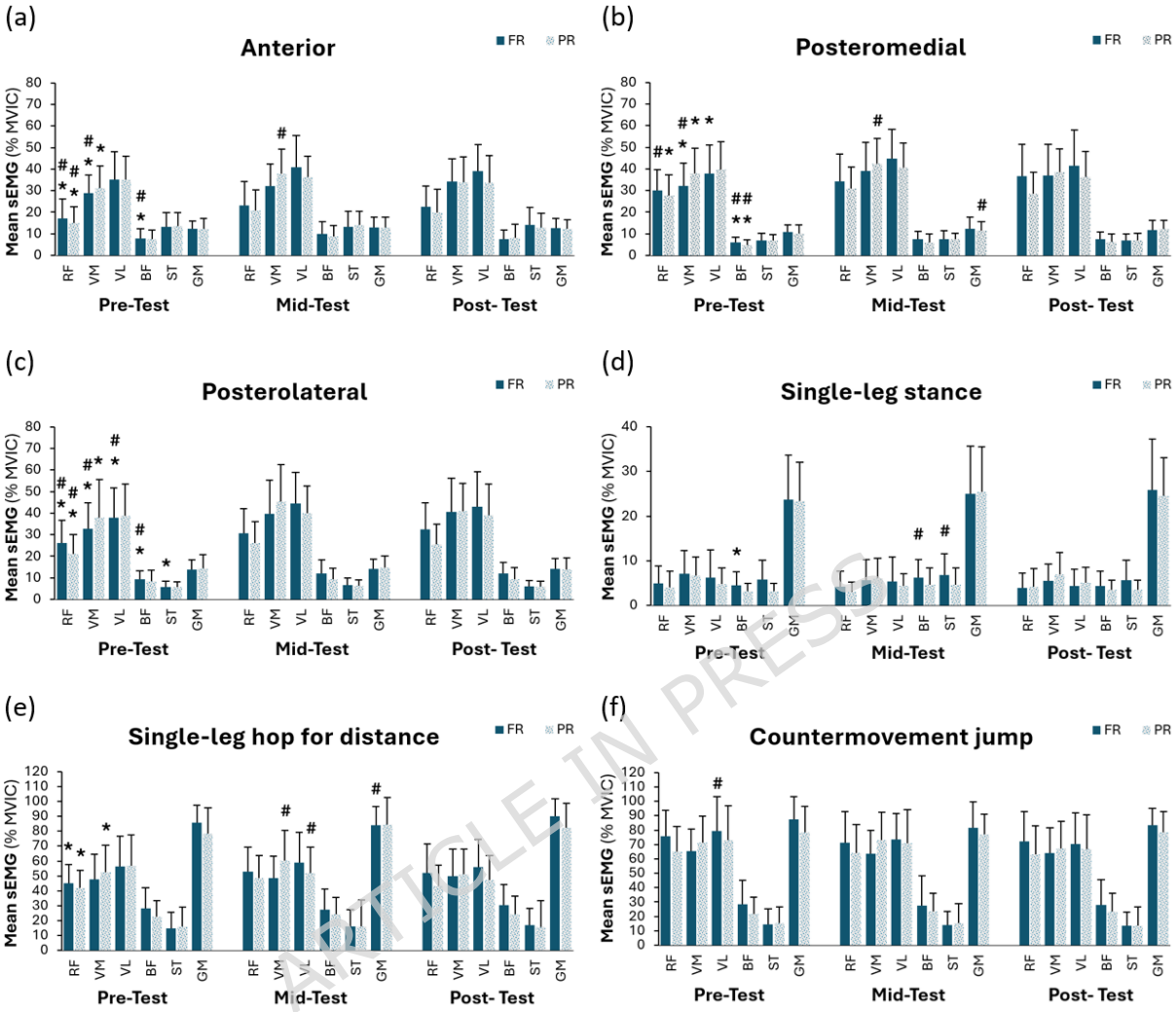


Figure 4. Mean ± SD sEMG activity of all muscles for the FR and PR groups at pre-test, mid-test, and post-test time points. Panels show sEMG activity during the reaching phase of the Y-Balance test in the (a) anterior, (b) posteromedial, and (c) posterolateral directions; (d) throughout the stance phase of the single-leg stance test; (e) during the propulsion phase of the single-leg hop distance test normalized to leg length; and (F) during the propulsion phase of the countermovement jump. Significant within-group pairwise comparisons from post-hoc tests are indicated by symbols (* = $p < 0.05$, significantly different from mid-test; # = significantly different from post-test).