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# POST-FATIGUE RECOVERY OF STRENGTH, BALANCE AND PERFORMANCE FOLLOWING LOCAL MUSCLE VIBRATION VERSUS PASSIVE REST IN SOCCER PLAYERS: A RANDOMIZED CONTROLLED TRIAL

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**LEVEL OF EVIDENCE:** 1b

## ABSTRACT

*Background:* Quadriceps fatigue compromises soccer performance and safety. This RCT tested whether local muscle vibration (LMV) provides superior recovery versus passive rest for strength, dynamic balance, and hop performance post-fatigue in semi-professional players.

*Methods:* Twenty-six male soccer players (control group: 26.84 ± 4.52 years; LMV group: 25.85 ± 5.36 years) were randomly assigned to either the control (n = 13) or LMV group (n = 13). After a quadriceps fatigue protocol, the LMV group received 2 minutes of 60 Hz local vibration, while the control group rested passively for the same duration. Quadriceps maximal voluntary contraction (MVC), single-leg hop test, and Y-balance test were assessed at baseline, post-fatigue, and post-intervention/rest. Two-way repeated measures ANOVA was used for analysis.

*Results:* MVC declined post-fatigue (LMV: $p = 0.005$, Cohen's $d = 0.76$; control: $p = 0.004$, Cohen's $d = 0.80$), with LMV showing better recovery ($p = 0.004$, Cohen's $d = 0.80$) versus control ($p = 0.046$, Cohen's $d = 0.55$). Single leg hop improved post-LMV ($p = 0.010$, Cohen's $d = 0.71$). Y-balance test improvements occurred in anterior reach (LMV: $p = 0.012$, $d = 0.50$), posteromedial (LMV: $p = 0.039$; control: $p = 0.002$), posterolateral and composite scores (all $p \leq 0.002$, with medium to large effect sizes).

*Conclusion:* LMV produced superior recovery versus passive rest, with complete strength restoration, improved hop performance, and improved anterior dynamic balance. These improvements are likely due to enhanced muscle activation and better motor control following vibration. As a non-invasive intervention, LMV shows clinical utility for athletic recovery. The findings support its integration into sports rehabilitation, pending further investigation of optimal protocols across athletic populations.

## KEYWORDS

Vibration, fatigue, quadriceps muscle, performance, balance, recovery

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## INTRODUCTION

The quadriceps muscle plays a central role in lower limb function and is primarily engaged in activities such as kicking, jumping, and cycling. However, quadriceps injuries (e.g., strain and tears) are common among athletes, particularly in sports like football and rugby players. These injuries, along with reduced muscle function, can negatively impact lower limb mechanics and overall athletic performance. Also, quadriceps muscle fatigue may increase the risk of knee joint injuries[1-3]. Soccer players frequently experience localized fatigue in the quadriceps, hamstrings, and tensor fasciae latae muscles[4]. Quadriceps muscle fatigue negatively impacts kinematic variables and the accuracy of corner kicks in soccer players[5]. Additionally, quadriceps fatigue reduces neuromuscular and sensorimotor control, impairs dynamic balance, and may increase the risk of lower extremity injuries[6]. Fatigue is defined as the difficulty in initiating or maintaining voluntary activities or the progressive reduction in maximum voluntary force produced by one or a group of muscles[7]. One of the most significant effects of fatigue appears to be the reduction in proprioception, attributed to changes in muscle spindle receptor function[8]. Additionally, fatigue diminishes the ability to generate maximum force, impacting strength, speed, and jumping performance during competition and even up to five days after training. This can result in poor performance and an increased risk of injury[9,10]. Muscle fatigue activates pain receptors due to the accumulation of lactic acid and creatine kinase[11].

On the other hand, balance is essential for soccer players to maintain stability during actions such as dribbling, shooting, and tackling. Good balance improves agility and coordination, helping to reduce the risk of injury. Additionally, proper neuromuscular control, core strength, and proprioception are critical for maintaining both dynamic and static balance. Interventions such as massage, compression garments, active recovery, cryotherapy, whole-body vibration, and dry needling are recommended for short-term recovery and sustaining maximum performance after fatigue[12-14]. Local muscle and whole-body vibration are other suggested interventions that enhance blood flow, facilitate tissue repair, and support the formation of vascular networks[15,16].

However, these approaches have shown controversial results and limited evidence. Greco's study found no significant effect of whole-body vibration on fatigue index[17]. Other studies have reported increased muscle activity following vibration[18]. Another study reported that vibration therapy effectively reduced muscle fatigue and/or fatigue accumulation in elite athletes during intensive training seasons[19]. There is also evidence supporting the positive effects of whole-body vibration on performance recovery, pain reduction, and maximum voluntary isometric leg extension[20]. Recent research indicates that local muscle vibration can improve static and dynamic balance in patients with ankle instability[21]. However, there is limited evidence on the use of local muscle vibration (LMV) as a convenient, cost-effective, and portable intervention for quadriceps muscle fatigue, particularly in enhancing balance and performance in soccer players.

Our study aimed to compare the effects of LMV versus passive rest on post-fatigue recovery of quadriceps strength (maximal voluntary contraction) (MVC), dynamic balance (Y-balance test), and functional performance (single-leg hop) in semi-professional male soccer players. We hypothesized that LMV would lead to significantly greater recovery of strength, balance, and performance measures compared to passive rest following quadriceps fatigue induction.

## METHODS

### Study design and participants

This single-blinded randomized controlled trial, approved by the Ethics Committee of Tehran University of Medical Sciences (IR.TUMS.FNM.REC.1402.006) and registered in the Iranian Registry of Clinical Trials (IRCT20230325057773N1; September 12, 2023). All 26 participants (aged 18–35 years) were healthy semi-professional male soccer players, meaning they receive payment for playing but do not do it as their full-time job. They trained at least three times per week to keep a similar training level. Participants were included if they had no recent lower limb injuries or neuromuscular/cardiovascular disorders, and were excluded for intense non-soccer sports, inability to complete the protocol, or acute illness. The sample size was derived from a prior study[22]. The study duration was 2 months. Participants provided written informed consent, completed baseline questionnaires, and attended the Sports Biomechanics Laboratory at the school of rehabilitation of Tehran University of Medical Sciences for one pre-testing session and two test sessions (pre- and post-fatigue protocol) *(Fig. 1)*.

### Randomization

Participants were randomly allocated to either the LMV group or the Control group using a simple randomization procedure. The researcher (who was not involved in testing) prepared 26 opaque envelopes—half labeled "LMV" and half "Control"—and shuffled them thoroughly. Each participant blindly selected one envelope to determine their group assignment.

### Intervention

Vibration was administered using a Thrive handheld vibrator (Thrive 717A, Tokyo, Japan) applied to the midline of the dominant quadriceps muscle. The dominant side refers to the leg primarily used for kicking the ball or for standing while performing balance-requiring tasks[23]. This was the right leg for 22 out of the 26 participants. All subsequent testing (MVC, hop test, Y-balance) was performed on this same dominant limb. The vibration frequency was set at 60 Hz, which is the only option

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available on the device used in this study. This frequency was chosen because it falls within the effective range (30 to 90 Hz) shown in previous research to trigger neuromuscular responses. Lower frequencies within this range may also work well regardless of how long the treatment lasts[24]. Thus, we opted for a 2-minute application based on our prior study protocol. In contrast, the control group rested for 2 minutes without engaging in physical activity after the fatigue protocol.

The intervention began with familiarization of the participants to three outcome measures. A five-minute warm-up was performed, including standing heel raises, 30 half squats, 5 vertical jumps, 5 soft volleyball court runs, and 30 seconds of stretching for the quadriceps and hamstrings. Participants were assessed pre-fatigue, immediately post-fatigue, and post-2 minutes of rest or vibration. The pre-fatigue tests included the single leg hop test and Y-balance test. The MVC of the quadriceps muscle was measured using an isokinetic dynamometer (Biodex Medical, Shirley, New York, USA). Participants were instructed to exert maximum effort during each test, and the average of three efforts was recorded. To induce fatigue, participants performed knee extensions as isometric contractions at 60 degrees of knee flexion, using 40% of their initial MVC torque[1]. They were encouraged to maintain the contraction until the torque dropped to 50% of the initial value. If the participant was unable to restore the torque to more than 50% of the initial value within three seconds, the protocol was considered complete, marking the point of fatigue.

At this point, the procedure was stopped, and post-fatigue tests were conducted in the following order: MVC of the quadriceps muscle, single leg hop test, and Y-balance test. The results were recorded by an assessor who was blinded to the participants' group allocation, leaving the experiment site to remain unaware of whether LMV or rest was administered. In the LMV group, participants immediately received local vibration applied to the midline of the quadriceps on the dominant side, with a frequency of 60 Hz for 2 minutes. In contrast, the Control group rested for 2 minutes without engaging in physical activity. After the intervention/rest period, the assessor returned to the research location, and post-intervention/rest tests were conducted in the order of the single leg hop test, Y-balance test, and quadriceps MVC, with results recorded accordingly. All testing was done between 2 PM and 5 PM for consistency.

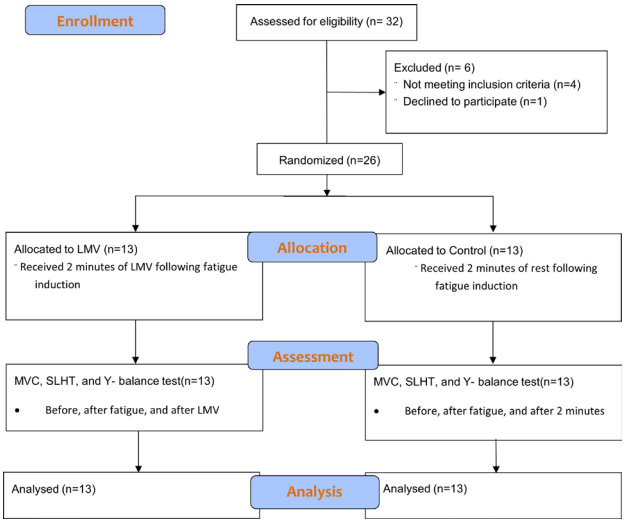



***Figure 1.*** *CONSORT flow diagram of the study. Abbreviations: LMV, local muscle vibration; MVC, maximum voluntary contraction; SLHT, single-leg hop test.*

## Outcome assessments

### *MVC of the quadriceps muscle*

The MVC of the quadriceps muscle was assessed using an isokinetic dynamometer (Biodex Medical Systems 3 Inc., Shirley, New York, USA). Participants were seated on the dynamometer seat, holding handles on both sides, and secured with special straps from the pelvis to the shoulder and the upper front part of the dominant leg. The knee was positioned at 60 degrees of flexion, and the device was set in isometric mode, aligning the mechanical axis of the dynamometer with the anatomical axis of the knee *(Fig. 2)*. Participants performed three isometric contractions, each lasting five seconds, exerting maximum effort to extend the knee. A 15-second rest interval separated each effort. The dynamometer recorded the maximum torque generated during these contractions. The average of the three maximum torque values was calculated and used for analysis

### *Single leg hop test*

Hop testing is a valuable predictor, commonly used




***Figure 2.*** *Local muscle vibration application on the quadriceps (left) and participant positioning for maximum isometric torque assessment and fatigue induction (right).*

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as a practical, performance-based measure. It assesses neuromuscular control, strength, and confidence in the limb.

These tests simulate dynamic knee stability during sports activities, helping to prepare patients for a safe return to play. The participant stood on their dominant leg and performed either one or three hops as far as possible along a straight line, landing on the same foot. They were instructed to jump forward and cover as much distance as possible, with both hands kept behind their backs to prevent momentum generation. The test was performed three times, and the average of the three values was calculated. The distance of each jump is measured in meters from the back of the heel at the starting point to the back of the heel after landing. For a correct and successful test, the participant must maintain balance on the same leg after landing until the assessor marks the landing point. This test was repeated three times, with a 15-second interval between each repetition, and the average score of the three attempts was calculated and recorded for further analysis[25].

### *Y-balance test*

The Y-balance test is a reliable test designed to assess dynamic balance and assess a person's risk of injury[26]. This test evaluates dynamic balance across three directions: anterior, posteromedial, and posterolateral, with the posteromedial and posterolateral directions positioned at a 135-degree angle relative to the anterior direction. The Y-balance composite score (%) was calculated as the average of normalized reach distances relative to limb length. The participant stands on their dominant leg at the center of three lines with hands placed on their trunk. They attempt to reach as far as possible with the opposite foot in each of the three directions while maintaining balance on the dominant leg. The distance from the center point to the farthest reach in each direction is measured in meters using a measuring tape. The test is repeated three times with a 15-second rest interval. The test is considered invalid if the participant loses balance while standing on one leg, uses their hands for support, or fails to maintain contact with the opposite leg throughout the test. In such cases, the test is repeated. Participants are allowed up to six

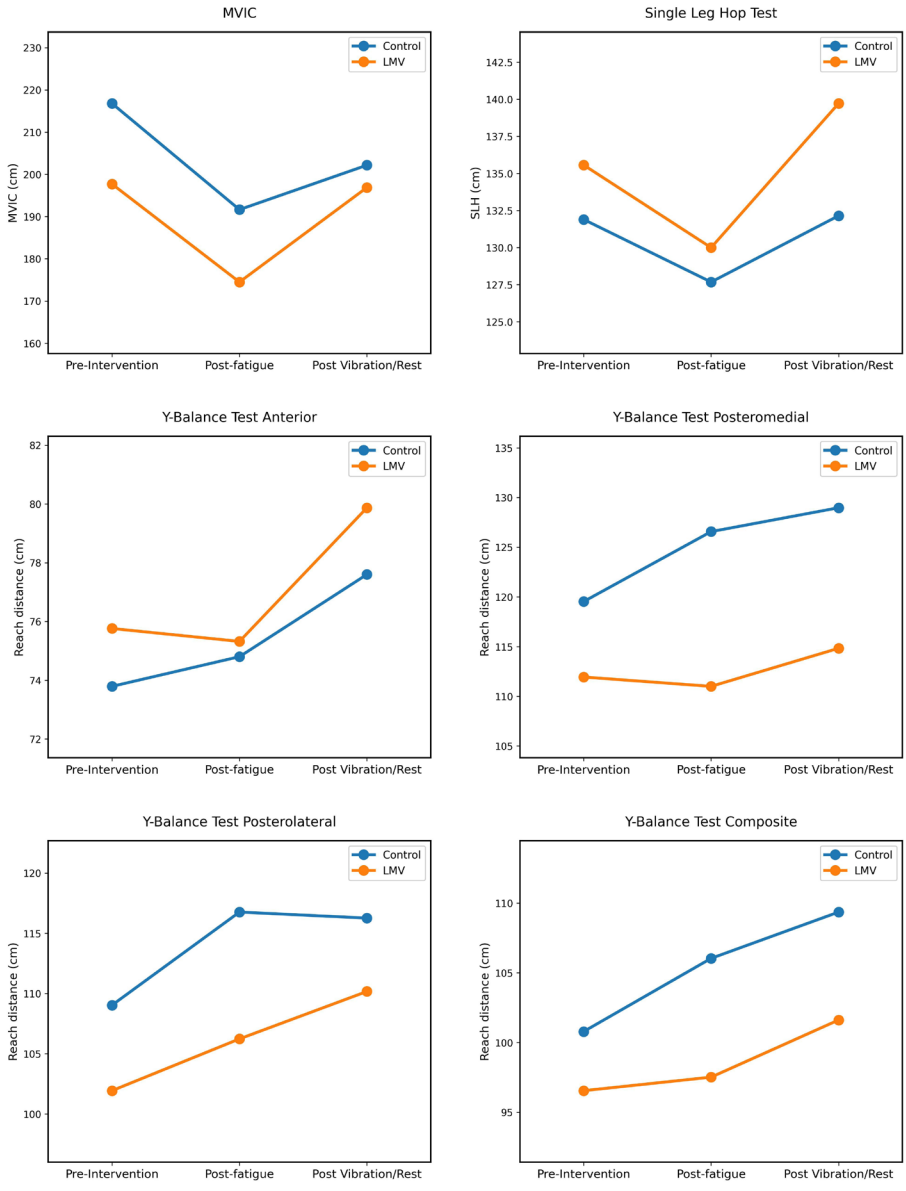



***Figure 3.*** *Changes in outcome measures across assessment timepoints for the local muscle vibration and control groups.*

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attempts to complete the test correctly, aiming to obtain three acceptable attempts in each direction. The average reach distance for each participant is normalized to their leg length by dividing by their lower limb length and multiplying by one hundred[21].

## Statistical analysis

Data analysis was conducted using SPSS version 25. The normality of the data was confirmed by the Shapiro-Wilk test. Based on this, a two-way repeated measures ANOVA was applied to assess the main effects of group, time, and their interaction on the outcome measures. Pairwise comparisons were performed using Bonferroni tests to examine the significant differences between time points within each group. The effect size was determined using Cohen's d, with statistical significance set at $p < 0.05$. Cohen's d values were interpreted as small (Cohen's d = 0.2), medium (Cohen's d = 0.5), and large (d ≥0.8)[27].

## RESULTS

*Table 1* presents participant demographics for both control and LMV groups, while *Table 2* shows outcome measures at baseline, post-fatigue, and post-intervention for each group. The two-way repeated measures ANOVA showed significant time effects across multiple measures, with MVC showing significant fatigue-induced declines in both the LMV (Δ% = -11.7%, p = 0.005, Cohen's d = 0.76) and control groups (Δ% = -11.6%, p = 0.004, Cohen's d = 0.80), though the LMV group demonstrated superior recovery post-vibration (Δ% = +12.8%, p = 0.004, Cohen's d = 0.80) compared to the control's partial recovery after rest (Δ% = -6.7%, p = 0.046, Cohen's d = 0.55). While single leg hop performance showed no group differences, a significant time effect (p = 0.01, Cohen's d = 0.17) appeared, with the LMV group improving 7.5% (p = 0.010, Cohen's d = 0.71) post-vibration. Y-balance tests showed directional improvements: anterior reach increased 6.0% (p = 0.012, Cohen's d = 0.50) post-vibration in the LMV group; posteromedial reach improved 3.4% (p = 0.039, Cohen's d = 0.57) in LMV and 7.9% (p = 0.002, Cohen's d = 0.86) in controls post-rest; and posterolateral reach showed improvements in both groups (LMV: Δ% = +8.1%, p = 0.001, Cohen's d = 0.48; Control: Δ% = +7.1%, p = 0.002, Cohen's d = 0.85). Composite scores improved significantly in both groups (LMV: Δ% = +5.3%, p = 0.002, Cohen's d = 0.59; Control: Δ% = +8.5%, p = 0.002, Cohen's d = 0.59), though interaction effects were only significant for posteromedial reach (p = 0.03, Cohen's d = 0.14), suggesting vibration improved recovery selectively *(Table 3 and Table 4, Fig. 3)*.

| Variable | Control (n=13) | LMV (n=13) |
|---|---|---|
| **Age (year)** | 26.84 ± 4.52 | 25.85 ± 5.36 |
| **Height (cm)** | 179.08 ± 4.78 | 176.9 ± 5.38 |
| **Weight (kg)** | 87.12 ± 14.42 | 80.21 ± 17.06 |
| **BMI (kg/m²)** | 27.14 ± 4.27 | 25.46 ± 4.23 |

***Table 1.*** *Participants characteristics.*
*Abbreviation: LMV, local muscle vibration.*

## DISCUSSION

This study assessed the effects of LMV on post-fatigue recovery of hamstring function in healthy young semi-

| Outcome measure | Group | Baseline | After fatigue | After vibration/rest |
|---|---|---|---|---|
| **MVC (Nm)** | Control | 216.8 ± 22.09 | 191.65 ± 29.29 | 202.18 ± 36.66 |
| | LMV | 197.71 ± 65.88 | 174.5 ± 69.15 | 196.9 ± 63.75 |
| **Single leg hop (cm)** | Control | 131.9 ± 16.02 | 127.68 ± 22.01 | 132.15 ± 19.88 |
| | LMV | 135.57 ± 24.58 | 130 ± 23.94 | 139.72 ± 20.44 |
| **Y-balance test (anterior) (cm)** | Control | 73.79 ± 7.45 | 74.8 ± 7.46 | 77.6 ± 9.82 |
| | LMV | 75.76 ± 9.28 | 75.32 ± 9.12 | 79.87 ± 8.73 |
| **Y-balance test (PM) (cm)** | Control | 119.53 ± 7.83 | 126.57 ± 6.11 | 128.97 ± 7.19 |
| | LMV | 111.94 ± 12.38 | 111 ± 14.44 | 114.83 ± 19.01 |
| **Y-balance test (PL) (cm)** | Control | 109.03 ± 8.08 | 116.76 ± 10.06 | 116.26 ± 11.08 |
| | LMV | 101.93 ± 16.77 | 106.23 ± 17.25 | 110.17 ± 16.36 |
| **Y-balance test (composite) (cm)** | Control | 100.79 ± 5 | 106.04 ± 5.14 | 109.36 ± 10.17 |
| | LMV | 96.55 ± 11.39 | 97.52 ± 11.49 | 101.62 ± 12.53 |

***Table 2.*** *Descriptive statistics at baseline, post-fatigue, and post-intervention (vibration for LMV group or rest for control group).*
*Abbreviation: MVC, maximal voluntary contraction; PM, posteromedial; PL, posterolateral; LMV, local muscle vibration.*

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| | | MVC | Single leg hop | Y-balance (anterior) | Y-balance (PM) | Y-balance (PL) | Y-balance (composite) |
|---|---|---|---|---|---|---|---|
| **F ratio** | Group | 0.50 | 0.32 | 0.27 | 8.03 | 2.32 | 3.63 |
| | Time | 15.49 | 5.02 | 6.22 | 8.01 | 19.67 | 16.84 |
| | Interaction | 1.41 | 0.71 | 0.28 | 3.82 | 1.61 | 1.88 |
| **p value** | Group | 0.49 | 0.58 | 0.61 | 0.01 | 0.14 | 0.07 |
| | Time | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| | Interaction | 0.25 | 0.50 | 0.76 | 0.03 | 0.21 | 0.18 |
| **Cohen's d** | Group | 0.02 | 0.01 | 0.01 | 0.25 | 0.09 | 0.13 |
| | Time | 0.39 | 0.17 | 0.21 | 0.25 | 0.45 | 0.41 |
| | Interaction | 0.06 | 0.03 | 0.01 | 0.14 | 0.63 | 0.07 |

***Table 3.*** *Main and interaction effects of group and time (two-way repeated measure ANOVA).*

*Abbreviation: MVC, maximal voluntary contraction; PM, posteromedial; PL, posterolateral. Bold values indicate statistically significant differences (p< 0.05).*

professional male soccer players, comparing its efficacy to passive rest. Our key findings show that LMV facilitated superior recovery of MVC and dynamic balance compared to controls, while both groups showed improvements in Y-balance test performance. These results support our hypothesis that neuromuscular vibration would improve recovery of strength and functional performance following fatigue induction

The MVC of the quadriceps muscle decreased after fatigue in both the LMV and control groups. However, in the LMV group, MIT significantly increased following vibration, with a large effect size. In contrast, the control group showed no significant increase in MIT after rest compared to the post-fatigue measurements. Consequently, complete fatigue recovery was not achieved in the control group. This outcome may be attributed to the activation of muscle spindles and large α-motoneurons, the dilation of muscle capillaries, improved muscle substance exchange and metabolism, as well as increased resistance to and recovery from fatigue[16,28-30]. These physiological mechanisms likely contributed to the observed 12.8% MVC recovery in the LMV group versus only 6.7% in controls. Our findings align with previous studies that have reported positive effects of vibration on voluntary muscle activation, peak isometric torque of knee extensors, maximal rate of force rise, and overall muscle performance[31,32]. However, despite these reported benefits, some studies have presented conflicting results regarding the effects of vibration. These include inconsistent findings on its impact on the MVC of the quadriceps, reduction in muscle weakness, and even negative effects on muscle fatigue or weakness[33,34]. The discrepancy may stem from methodological differences in vibration parameters or population characteristics. In the present study, there was no significant main effect of the group; however, our results indicated a prominent reduction in fatigue following LMV, with greater improvements observed compared to the control. These findings may be attributed to factors such as the type of participants, their age, the short duration of LMV application, or the sample size.

For single leg hop test performance, the LMV group demonstrated a significant and positive effect on improving SLHT performance, an indicator of performance score, compared to post-fatigue results (Δ% = +7.5%). Conversely, no significant increase in performance score was observed after rest compared to post-fatigue. These findings may be attributed to the beneficial effects of LMV on fatigue recovery, including enhanced muscle activation, increased motor unit recruitment, improved proprioception, and modulation of spinal reflex excitability. Similar results have been previously reported that local vibration significantly increased erector spinae muscle activity at the lumbar level[35]. Similarly, another study found that both holistic and local vibrations effectively alleviated muscle fatigue in elite athletes during intensive training[19]. The observed 7.5% improvement in hop distance with LMV with large effect size indicates clinically meaningful functional recovery, while the control group's non-significant change further highlights vibration's efficacy.

For the Y-balance test scores in the anterior (Δ% = +6.0%), posteromedial, and composite directions (Δ% = +5.3%) significantly increased following LMV, with medium to large effect sizes compared to post-fatigue results. Conversely, no significant changes were observed in the control group. These findings suggest that LMV may increase proprioceptive feedback, improve muscle activation, and modulate sensorimotor integration, thereby contributing to improved dynamic balance in fatigued quadriceps muscles. However, the literature presents mixed findings due to variations in experimental designs, including differences in fatigue protocols and LMV parameters such as frequency, amplitude, and duration. While some

| Variable | Group | Pairwise comparison | Sig. | Mean Diff (Δ%) | Cohen's d |
|---|---|---|---|---|---|
| **MVC** | LMV | Baseline – after fatigue | 0.005 | -11.70 | 0.76 |
| | | Baseline – after vibration | 0.650 | -0.40 | 0.12 |
| | | After fatigue – after vibration | 0.004 | 12.80 | 0.80 |
| | Control | Baseline – after fatigue | 0.004 | -11.6 | 0.80 |
| | | Baseline – after rest | 0.046 | -6.70 | 0.55 |
| | | After fatigue – after rest | 0.116 | 5.50 | 0.43 |
| **Single Leg Hop** | LMV | Baseline – after fatigue | 0.116 | -4.10 | 0.43 |
| | | Baseline – after vibration | 0.442 | 3.10 | 0.21 |
| | | After fatigue – after vibration | 0.010 | 7.50 | 0.71 |
| | Control | Baseline – after fatigue | 0.152 | -3.20 | 0.39 |
| | | Baseline – after rest | 0.916 | 0.20 | 0.02 |
| | | After fatigue – after rest | 0.184 | 3.50 | 0.36 |
| **Y-balance test (anterior)** | LMV | Baseline – after fatigue | 0.083 | -0.60 | 0.05 |
| | | Baseline – after vibration | 0.051 | 5.40 | 0.45 |
| | | After fatigue – after vibration | 0.012 | 6.0 | 0.50 |
| | Control | Baseline – after fatigue | 0.526 | 1.40 | 0.13 |
| | | Baseline – after rest | 0.091 | 5.20 | 0.44 |
| | | After fatigue – after rest | 0.071 | 3.70 | 0.32 |
| **Y-balance test (PM)** | LMV | Baseline – after fatigue | 0.600 | -0.80 | 0.14 |
| | | Baseline – after vibration | 0.182 | 2.60 | 0.36 |
| | | After fatigue – after vibration | 0.039 | 3.40 | 0.57 |
| | Control | Baseline – after fatigue | 0.002 | 5.90 | 0.86 |
| | | Baseline – after rest | 0.002 | 7.90 | 0.86 |
| | | After fatigue – after rest | 0.249 | 1.90 | 0.31 |
| **Y-balance test (PL)** | LMV | Baseline – after fatigue | 0.004 | 4.20 | 0.25 |
| | | Baseline – after vibration | 0.001 | 8.10 | 0.48 |
| | | After fatigue – after vibration | 0.071 | 3.70 | 0.23 |
| | Control | Baseline – after fatigue | 0.002 | 7.10 | 0.85 |
| | | Baseline – after rest | 0.001 | 6.60 | 0.74 |
| | | After fatigue – after rest | 0.839 | -0.40 | 0.05 |
| **Y-balance test (Composite)** | LMV | Baseline – after fatigue | 0.294 | 1.00 | 0.20 |
| | | Baseline – after vibration | 0.002 | 5.30 | 0.59 |
| | | After fatigue – after vibration | 0.023 | 4.20 | 0.44 |
| | Control | Baseline – after fatigue | 0.002 | 5.20 | 0.60 |
| | | Baseline – after rest | 0.002 | 8.50 | 0.59 |
| | | After fatigue – after rest | 0.075 | 3.10 | 0.34 |

***Table 4.*** *Paired comparisons of outcome measures for each group.*

*Abbreviation: PM, posteromedial; PL, posterolateral; LMV, local muscle vibration. Bold values indicate statistically significant differences (p< 0.05).*

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studies report positive effects, others show minimal or no significant improvements in muscle force production, power, performance, or balance[36,37]. Additionally, previous studies have shown that five minutes of rest or vibration following fatigue significantly improved one-leg stance time in both groups, with the experimental group demonstrating greater improvements compared to the control group[38]. Based on the positive effects of LMV on performance and YBT following quadriceps fatigue, incorporating this modality into rehabilitation programs could be beneficial for improving neuromuscular control and reducing the risk of lower limb injuries. Additionally, individual responses to LMV may vary depending on factors such as training status, age, and injury history. Therefore, studies investigating the interactive effects of LMV and fatigue on dynamic balance could offer valuable insights into potential rehabilitation strategies and training interventions. The underlying mechanisms may include improved muscle activation and proprioception, alongside changes in motor unit recruitment and spinal reflex excitability[35]. Vibration has shown effectiveness for post-exercise recovery[19], supporting LMV as practical recovery tool for athletes and clinicians.

However, further research is essential to establish optimal protocols and identify specific populations that may benefit most from LMV. The improvements seen in the control group, especially in the posteromedial direction, might be due to motor learning from repeated testing, natural recovery from fatigue, or getting used to the test procedure. While our results show statistically significant improvements, the lack of established Minimal Clinically Important Difference (MCID) values for the Y-Balance test in this group makes it hard to know the true clinical significance of these changes. It is important to note that a composite score below 89% is linked to a higher risk of injury. In our study, all scores were above this limit, showing that participants stayed in a lower-risk category even after fatigue. The improvements with LMV may represent a movement further away from this risk level, suggesting it could be practically useful.

This study has several limitations. First, it was conducted in a controlled laboratory setting, which may restrict the generalizability of the findings to real-world athletic environments. Second, the testing protocol included three assessment stages (immediate, short-delay, and long-delay post-intervention), which—despite participant familiarization—may have introduced timing-related variability and potential learning effects. Third, due to time constraints, vibration was applied to a single muscle region only, which prevented assessment of broader LMV effects. We also did not include any medium or long term follow up to see how long the benefits last, and the person doing the measurements was not always blinded to the treatment. Future studies should use longer follow up periods, incorporate full blinding of assessors, and include larger and more diverse groups of athletes to confirm our results.

## CONCLUSION

This study indicates that LMV effectively improves post-fatigue recovery in athletes, outperforming passive rest by fully restoring muscle strength, improving hop performance, and improving dynamic balance. These benefits likely mediate from LMV's ability to activate muscles and improve neuromuscular control, making it a practical, non-invasive recovery tool for athletes and clinicians. While individual responses may vary and optimal protocols require additional investigation, our findings support incorporating LMV into rehabilitation and training programs to accelerate recovery and potentially reduce injury risks. Future research should examine protocol efficacy across different athletic disciplines and competitive levels to develop evidence-based implementation frameworks.

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