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Research Article

Comparing vastus lateralis:vastus medialis activation ratios in the concentric and eccentric phases of unilateral multi-joint exercises

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HIGHLIGHTS

- Multi-joint exercises show similar vasti activation on concentric phase
- The ratio is greater in the single-leg squat than in the forward lunge on eccentric phase
- All exercises showed a vasti muscle activation ratio below 1 in both phases
- This could suggest a higher vastus medialis activation than vastus lateralis during these exercises.

ABBREVIATIONS

BUL	Bulgarian squat
CEDE	Consensus for Experimental Design in Electromyography
EMG	Electromyographic
LUN	Lunge
MVICs	Maximal Voluntary Isometric Contractions
PFP	Patellofemoral pain
RMS	Root Mean Square
ROM	Range of Motion
SENIAM	Surface Electromyography for Non-Invasive Assessment of Muscles guidelines
SLS	Single-leg squat
VL	Vastus lateralis
VM	Vastus medialis

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BACKGROUND: Activation imbalances between the vastus lateralis (VL) and vastus medialis (VM) may contribute to patellar maltracking and dynamic knee valgus. Given that the VL tends to have a greater force production capacity than the VM, rehabilitation programs incorporating multi-joint bodyweight exercises that promote relatively higher VM activation may be particularly beneficial. However, the behavior of the VL:VM activation ratio during the concentric and eccentric phases of such exercises remains insufficiently explored.
AIM: To compare the VL:VM activation ratio during the concentric and eccentric phases of three unilateral multi-joint exercises: the single-leg squat (SLS), lunge (LUN), and Bulgarian squat (BUL).
METHODS: Twenty-five healthy volunteers (15 men) were monitored for VL and VM electromyographic (EMG) signal, while performing ten repetitions of each exercise. EMG data acquired during concentric and eccentric phases were normalized by the knee extensors' maximum voluntary isometric contraction. VL:VM ratio was determined by dividing the VL's EMG amplitude by the VM's EMG amplitude. Ratios greater than 1.0 indicated that the VL was more active than the VM.
RESULTS: No significant differences were found between-exercises in the VL:VM ratio during the concentric phase ($p=0.33$). However, we found the significant difference between-exercises only during the eccentric phase, where a higher VL:VM ratio was observed in the SLS (0.83 ± 0.41) compared to the LUN (0.70 ± 0.32) ($p=0.041$; effect size: 0.35) exercise.
INTERPRETATION: Although statistical differences favored the SLS over the LUN only during the eccentric phase, the small effect size and VL:VM ratios below 1 suggest that practitioners may consider all three exercises as effective strategies for muscle strengthening with greater activation of the VM compared to the VL.

KEYWORDS: EMG | Multi-joint | Vastus lateralis | Vastus medialis

INTRODUCTION

The quadriceps muscle is essential for performing several sports and daily life activities, as well as playing a crucial role in patellar stabilization [1,2]. Among the muscles that make up the quadriceps, the vastus lateralis (VL) and vastus medialis (VM) are monoarticular and work synergistically to stabilize the patella during dynamic knee extension [3]. Alterations in this synergy can modify patellar alignment, which appears to be one of the observed factors in individuals with patellofemoral pain [4]. One of the discussed aspects in this synergic action is the delayed activation of VM relative to VL in patients with patellofemoral pain [5], which has been associated with increased lateralization of the patella in these patients [6]. Another aspect concerns the balance of forces and activation between the vasti muscles [7]. Although an ideal VL:VM ratio is 1:1, different values (0.34–0.75) have been reported for this ratio [8], which seem to be associated with excessive dynamic knee valgus [9].

Based on this evidence regarding the imbalance between the vasti muscles, a condition more commonly observed in patients with patellofemoral pain [5], several studies have sought to identify the best exercises to mitigate these potential differences between the vasti muscles, particularly by increasing the VM's activation relative to the VL's [3,10,11]. One of the most common discussions involves open and closed kinetic chain exercises for knee extension, which present controversial results [12,13,14].

Another important aspect concerns the choice between bilateral and unilateral exercises. While closed kinetic chain exercises performed bilaterally have shown average VL:VM ratios of 1.07 [15] and 1.05 [16], the use of unilateral bodyweight exercises is more functional for daily life and sports activities, especially in sports that involve unilateral forces. In these cases, greater loads can be utilized when the exercise is performed unilaterally [17], a phenomenon explained by the so-called bilateral deficit [18]. EMG studies measuring the VL and VM during unilateral exercises commonly included in training programs typically report results separately for each muscle, expressed as a percentage of maximal voluntary contraction. When calculating the VL:VM ratio in these exercises, values close to 1 have been observed during single-leg squats (SLS) [19], lunges (LUN) [19] in the concentric and eccentric phases, and Bulgarian squats (BUL) [15]. However, one aspect that has been less explored in these studies is whether the VL:VM ratio behaves differently between the concentric and eccentric phases, given that the vasti muscles appear to behave differently during concentric and eccentric contractions [20]. This could alter the ratio between the vasti muscles depending on the type of contraction within the same exercise.

Therefore, the objective of our study was to compare the VL:VM EMG activation ratio during the concentric and eccentric phases of three multi-joint unilateral exercises: LUN, SLS and BUL.

METHODS

Participants

Men and women aged 18 to 40 years were recruited via social media and university campus advertisements. Individuals with a history of lower limb injuries, recent pain during squatting or jumping exercises in the past 12 months, or cardiovascular or neurological diseases were excluded. Participants' training levels were assessed through three questions: (i) the current duration of uninterrupted training; (ii) any periods of detraining; and (iii) previous training experience. Their training status was determined using a simple scoring system based on these responses, with an average score calculated from the three items. Classification criteria from a previous study [21] were used: (i) average score < 2: beginner; average score > 2 and < 3: intermediate; average score > 3 and < 4: advanced; and average score > 4: highly advanced.

The study adhered to the principles of the Declaration of Helsinki. All participants provided written consent after a detailed explanation of the procedures, and the study was approved by the university's ethics committee (approval number 5.596.115).

Study Design

Data collection was carried out in two sessions, with a minimum of seven days and a maximum of ten days between them to prevent any potential transfer effects. Participants were asked to wear their own comfortable shorts, t-shirts, and sports shoes, and to refrain from any lower limb exercises in the 24 hours leading up to the testing session.

Upon arriving at the university, participants began by performing 15 squats to prepare for the tests. During the first session, they were introduced to maximal voluntary isometric contractions (MVICs) of the knee extensor muscles and the exercises being investigated (LUN, SLS and BUL), with a five-minute interval between each exercise. They were also advised to maintain their usual exercise and diet routines during the interval between sessions.

In the second session, EMG data were collected from the VL and VM muscles during MVICs and the exercises. Participants performed the tests on their dominant leg, defined as the leg they would prefer to use for kicking a ball. The order of exercises was randomly determined using a randomized block design with the help of http://randomization.com [22].

Procedures

EMG Acquisition

To collect EMG data, a four-channel electromyograph (Miotool-400, Miotec - Biomedical Equipment, Porto Alegre, Brazil), sampling at 2000Hz with 14-bit resolution, was used in conjunction with specific data acquisition software (MiotecSuite - Biomedical Equipment, Porto Alegre, RS, Brazil) connected to a computer. Surface EMG measured the amplitude of the VL and VM muscles during MVICs for each of the three exercises. Following skin preparation, pairs of pre-amplified surface electrodes (radius 17.5 mm; inter-electrode distance = 2 cm; Descarpack, São Paulo, SP, Brazil) were applied according to the Surface Electromyography for Non-Invasive Assessment of Muscles guidelines (SENIAM, 2023). Additionally, a reference electrode was placed on the tibial tuberosity. All procedures complied with the Consensus for Experimental Design in Electromyography (CEDE) project [23].

Maximal Voluntary Isometric Contraction (MVIC)

For the MVIC, participants performed an isometric knee extension on one leg while sitting in a knee extension chair. They exerted force against the equipment's immovable arm, maintaining a knee flexion of 90°, with their trunk supported by the chair's backrest [24]. Participants were instructed to perform three 5-second MVICs, with a 2-minute rest interval between attempts to avoid fatigue. Verbal encouragement was provided during each attempt, and EMG amplitudes (using root mean square – RMS - values) of the VM and VL muscles were recorded [23].

Exercises

Participants were instructed to perform 10 repetitions for all exercises, incorporating both the eccentric and concentric phases through the full range of motion (ROM). A metronome set to 60 beats per minute controlled the exercise pace, with 2 beats allocated for each phase.

For the LUN exercise, participants began with both feet parallel on the ground. They then stepped forward with the dominant limb until the knee was flexed to 90°, making sure the rear knee did not touch the ground. Afterward, they returned to the initial standing position. The stride distance, marked on the floor for reference, corresponded to each participant's natural step and a half distance [19] (Figure 1A).

For the SLS exercise, participants initially kept both feet on the ground until the researcher gave a command. Upon receiving the command, they shifted their weight to the dominant side and flexed the opposite knee to 90°, maintaining a neutral hip position. They then performed knee flexion to the maximum depth, with arms crossed over the chest, and returned to the initial position while maintaining an upright trunk posture and facing forward [25] (Figure 1B).

For the BUL exercise, participants stood with one foot in front and the other behind, with the rear foot supported on a horizontal pressure bench. They crossed their arms over their chest and maintained an upright upper body, ensuring a natural balance in the lower back throughout the exercise. During the eccentric phase, individuals lowered their bodies until the front knee reached a 90° flexion angle. Then, in the concentric phase, they returned to the initial position by fully extending the front leg, while maintaining an upright trunk posture [26] (Figure 1C).

Data Analysis

EMG data were processed using a digital band-pass filter (5th order Butterworth; cut-off frequencies of 20-500 Hz) and smoothed with an RMS moving window of 150 ms. The RMS values during MVIC were calculated, with the highest value considered as 100% for each muscle. All data analysis was conducted by a single experienced evaluator using Miotec Suite software (version 1.0, Miotec - Biomedical Equipment, Porto Alegre, Brazil).

Exercises were recorded with a camera integrated into the EMG signal computer, positioned one meter from the participants in the sagittal plane. These recordings were used to determine the start and end of each exercise phase. The RMS value of each muscle during the three exercises was computed for the second, fourth, sixth, and eighth repetitions, covering both the concentric and eccentric phases of movement. The average RMS values for each phase were calculated for both muscles and normalized to their respective muscle-specific MVIC values, expressed as a percentage of MVIC [22]. The activation ratio was determined by dividing the VL EMG amplitude by the VM EMG amplitude (%MVIC), yielding the VL:VM ratio. Ratios greater than 1.0 indicated that the VL was more active than the VM muscle during either the concentric or eccentric phase of each exercise [6].

Statistical Analysis

The assumption of normality was assessed using the Shapiro–Wilk test. Sphericity was evaluated with Mauchly's test, and when the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied to adjust the degrees of freedom in the ANOVA. For comparing VL:VM ratio during the concentric and eccentric phases of each exercise, a repeated measures ANOVA was performed in each phase. When a significant effect of ANOVA was found, an LSD post-hoc analysis was performed to determine the differences. Effect sizes (partial η^2 and Cohen's d) were calculated for the ANOVA effects and for pairwise comparisons between exercises, respectively, when a significant ANOVA effect was observed. Cohen's criteria were used to interpret the results: $d > 0.20$ = small, >0.50 = moderate, >0.80 = large, and >1.30 = very large [27]. Results in the text and figures are presented as mean ± standard deviation. All statistical analyses were performed with SPSS 22.0 statistical package for Windows (SPSS Inc., Chicago, IL. USA) and significance was defined as $p<0.05$.

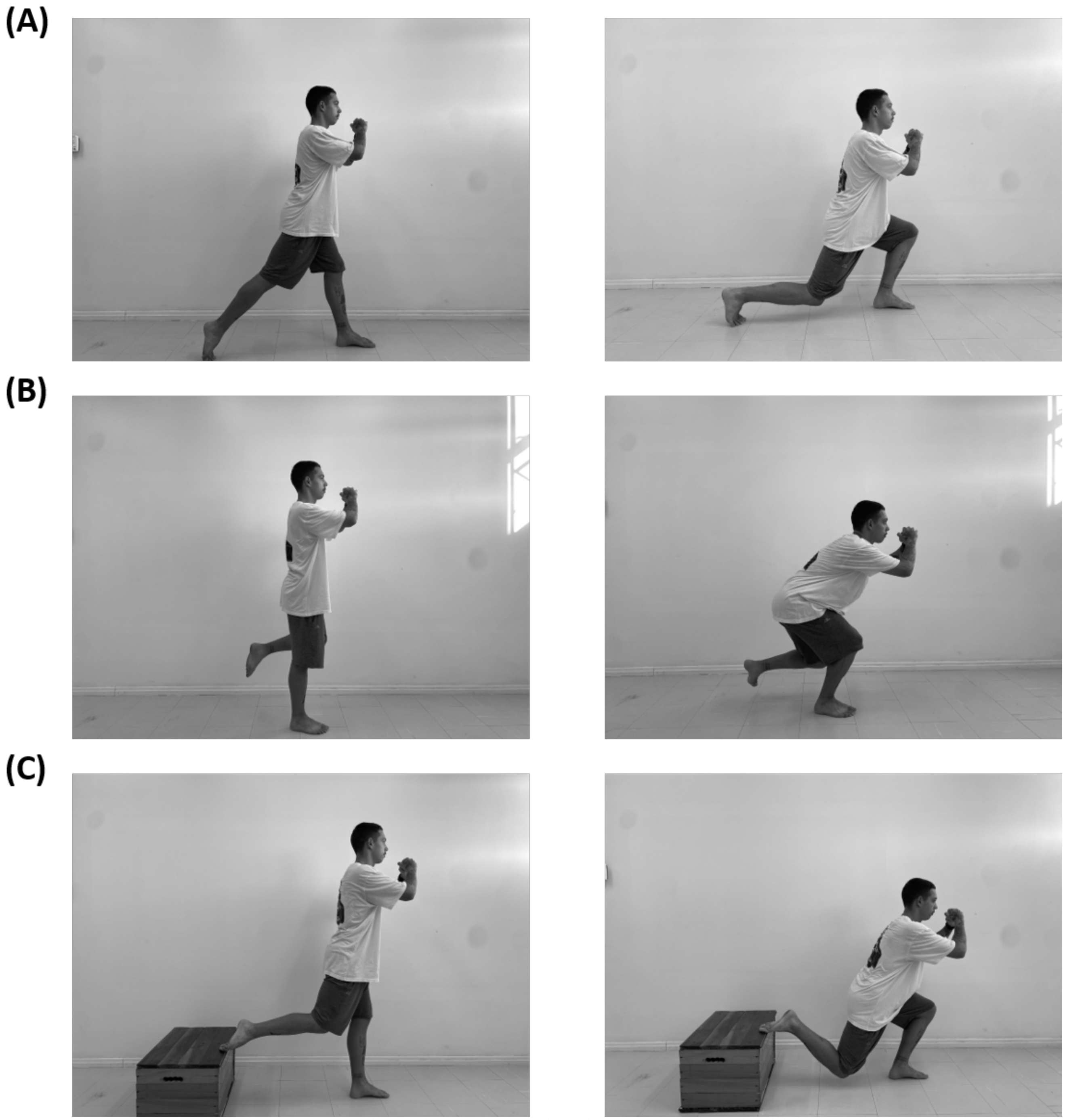

Figure 1. The analyzed exercises include the Forward Lunge (LUN) (A), Single-leg Squat (SLS) (B) and Bulgarian Squat (BUL) (C).

RESULTS

Twenty-five individuals (15 males, 10 females; age: 24.9 ± 6.4 years; body mass: 73.9 ± 15.4 kg; height: 1.70 ± 0.10 m; training status score: 3.2 ± 0.17 points) participated in the study. In terms of training status, 14 participants were classified as 'advanced', 6 as 'intermediate', 4 as 'highly advanced', and 1 as 'beginner'.

Regarding the VL:VM ratio during the concentric phase, no significant differences were found between exercises ($F_{(1.94,46.7)}$ = 1.11; p = 0.33; partial η^2 = 0.04; LUN: 0.74 ± 0.30; SLS: 0.78 ± 0.36; BUL: 0.76 ± 0.33). However, during the eccentric phase, a significant difference was observed between exercises ($F_{(1.31,31.6)} = 4.01$; $p = 0.043$; partial $\eta^2 = 0.14$). Specifically, the VL:VM ratio was higher in the SLS (0.83 ± 0.41) compared to the LUN (0.70 ± 0.32) ($p = 0.041$; *d* = 0.35), with no significant differences for the BUL (0.77 ± 0.34; *d* = 0.16) ($p = 0.09$) or between the LUN and BUL ($p = 0.10$; *d* = 0.21) (Figure 2).

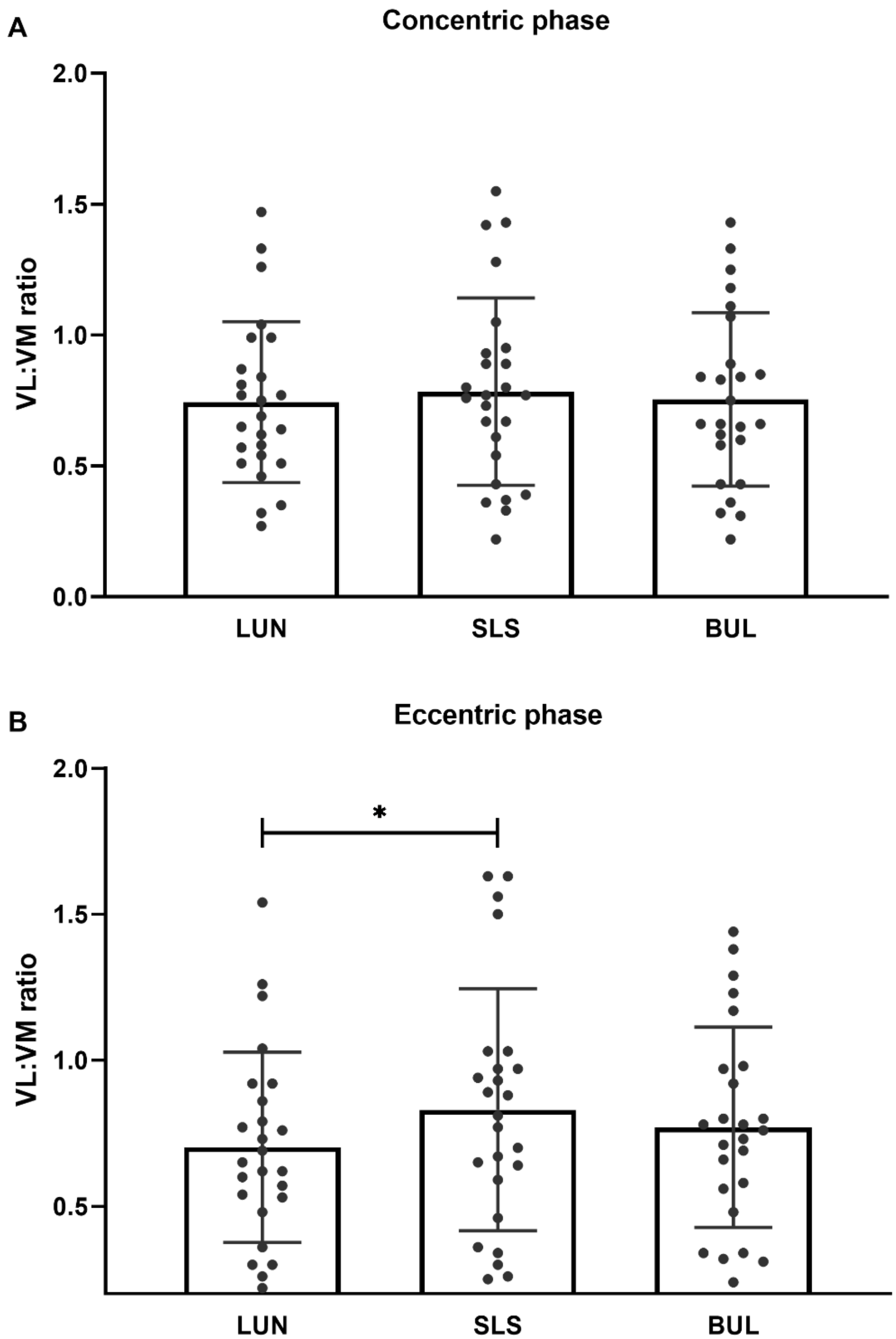

Figure 2. Comparison of the VL:VM ratio during concentric and eccentric phases between exercises * different between exercises. Each dot represents one participant. Legend: LUN = Lunge; SLS = Single-leg; BUL = Bulgarian Squat; VL = Vastus lateralis; VM = Vastus medialis.

DISCUSSION

This study aimed to compare the VL:VM activation ratio using EMG during the concentric and eccentric phases of the SLS, BUL and LUN exercises. We observed that the exercises showed similar ratios during the concentric phase. However, the SLS exhibited a significantly higher ratio compared to the LUN exercise during the eccentric phase, with a small effect size. Additionally, all the evaluated exercises displayed ratios below 1, indicating a superiority of VM over VL.

The VL and VM muscles work synergistically to stabilize the patella during dynamic knee extension [3], and alterations in this synergy can affect patellar alignment [4]. Previous studies have reported VL:VM ratios close to 1 during both the eccentric and concentric phases of SLS [19], BUL [15] and LUN [19] exercises, although a direct comparison of the ratios between these exercises has not been performed. In our study, a significantly higher VL:VM ratio was observed in the SLS compared to the LUN, but only during the eccentric phase. In contrast, a previous study that evaluated the concentric and eccentric phases of both LUN and SLS reported VL:VM ratios closer to 1 [19]. However, the aforementioned study used external loads (60% of 5RM), which may explain the discrepancy, as the use of external load likely increases VL contribution compared to bodyweight-only conditions [28]. Moreover, there is a mechanical difference between the exercises, as the SLS exhibits a higher knee extensor moment [29], while the LUN shows greater hip dominance [30]. Thus, the SLS requires greater quadriceps activation compared to the LUN [19].

Additionally, it is important to highlight the need for center of mass control during the eccentric phase, which increases the demand on the quadriceps in this exercise. Therefore, the higher VL:VM ratio observed in the SLS may be attributed to greater VL involvement, possibly due to a mechanical advantage of the VL over the VM, as the VL has a larger physiological cross-sectional area [7]. This implies a greater ability of the VL to generate force, causing the central nervous system to prioritize the muscle that produces the most force, resulting in higher VL activation compared to the VM in this exercise [7].

Although we found significant differences in the VL:VM ratio, with the SLS showing a significantly higher ratio compared to the LUN exercise during the eccentric phase, this difference exhibited a small effect size (d = 0.35), suggesting that it may not be clinically relevant enough to recommend one exercise over the other. Considering that individuals with patellofemoral pain exhibit reduced and delayed VM activation relative to the VL [5], exercises aimed at reducing these differences have been recommended for a long time. This is because the activation imbalance of the vasti muscles (greater involvement of the VL relative to the VM) is associated with worse patellar tracking in these individuals [4,6] and higher values of dynamic knee valgus [9], a biomechanical change associated with patellofemoral pain [31]. In both cases, VL:VM ratios exceeding 1 have been reported [4,6], which are considerably higher than those observed in our study. However, this imbalance in individuals with PFP shows substantial inter-individual variability, suggesting the existence of distinct neuromuscular strategies [8]. In line with previous studies, little is known about the impact of these specific coordination strategies on the development and persistence of painful musculoskeletal conditions, particularly in PFP [8]. Finally, it is important to note that the VL:VM activation ratio does not necessarily reflect the VL:VM force ratio, which may be more clinically relevant [32]. Furthermore, strengthening the hip muscles contributes to pain reduction and improved function in individuals with patellofemoral pain [33]. In this sense, all the exercises used in our study involve significant participation of the hip muscles [19,34], suggesting that they may be an effective alternative for strengthening the hip and quadriceps muscles, with greater activation of the VM compared to the VL.

Some limitations of this study should be taken into consideration: (i) the participants performed the exercises only with body weight, as they are simple exercises that can be executed in any environment; therefore, when performing the exercises with relative load (e.g., %1RM), there could be an influence on the study's results [28]; (ii) although the participants were instructed to perform the movement through the full range of motion, this was not measured during the exercises, limiting the comparison with other studies, as a greater range of motion could lead to increased muscle activation. It is worth noting that the study adhered to the recommendations of the Consensus for Experimental Design in Electromyography Project [23], ensuring high methodological quality.

CONCLUSION

Although statistical differences favored the SLS over the LUN only during the eccentric phase, the small effect size and VL:VM ratios below 1 suggest that practitioners may consider all three exercises as effective strategies for muscle strengthening with greater activation of the VM compared to the VL.

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