

Article

Comparative Analysis of Quadriceps Electromyography During Bodyweight Strength Exercises

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Featured Application

This study provides practical guidance for exercise selection in sports training and rehabilitation by describing the differential activation of the individual quadriceps femoris muscle bellies during commonly prescribed bodyweight exercises. The findings support evidence-based decision-making for clinicians and strength and conditioning professionals aiming to preferentially stimulate specific quadriceps components, thereby optimizing lower-limb strengthening, injury prevention, and functional recovery programs.

Abstract

Background: Although numerous exercises are prescribed for quadriceps femoris (QF) injury prevention and rehabilitation, few studies have compared QF muscle activation across commonly used bodyweight strength tasks. This study compared EMG activity of the rectus femoris proximal (RFP), rectus femoris medial (RFM), vastus lateralis (VL), and vastus medialis (VM) during seven bodyweight exercises with different stance positions. **Methods:** Twenty healthy male amateur football players performed three staggered-stance exercises (Split Squat, Bulgarian Split Squat, Backward Lunge), three parallel-stance exercises (Half-Squat, Russian Belt, Reverse Nordic), and one single-leg stance exercise (Lateral Step-Down). Surface EMG signals were recorded, and mean peak EMG values for each exercise were averaged and normalized to maximal isometric voluntary contraction (MVIC). **Results:** The highest VM and VL activation occurred during the Bulgarian Split Squat (VM: 85.4%; VL: 67.6% MVIC) and Backward Lunge (VM: 74.5%; VL: 59.9% MVIC). RFP and RFM showed the greatest activation during the Russian Belt (RFP: 49.8%; RFM: 39.6% MVIC) and Backward Lunge (RFP: 40.4%; RFM: 31.4% MVIC). VM and VL activation were significantly higher than RFP and RFM activation for all exercises except for Russian Belt and Reverse Nordic ($p < 0.005$). **Conclusions:** Exercises imposing greater knee stability demands preferentially activated VM and VL, whereas exercises with longer knee extensor lever arms maximized rectus femoris activation.

Keywords: anterior thigh; muscle activity; self-loading exercises; strength training



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1. Introduction

Quadriceps femoris (QF) injuries in football are most often muscle strains that occur during high-speed or high-force actions such as sprinting, kicking, and rapid changes of direction [1–6]. To prevent and rehabilitate such injuries, and to better understand their underlying mechanisms, surface electromyography (EMG) is widely used in sports science and rehabilitation to evaluate muscle activation in different exercises [7]. This non-invasive technique allows the analysis of the electrical activity of the muscles, providing information on activation, fatigue, and coordination during different activities [8]. When EMG signals are compared to peak activation during a maximal voluntary isometric contraction (MVIC), muscle activity can be expressed as a percentage of maximal theoretical activation [9]. This makes EMG a key tool for quantifying muscle involvement and understanding neuromuscular demands during different sport-specific tasks and rehabilitation exercises.

EMG have been widely used to analyze the activation levels of the QF bellies during the execution of lower limb strength exercises performed in different positions: (a) parallel stance, such as Squat exercises [10–19] (b) staggered stance, like Split Squats [20–22], Lunges [23,24] and Bulgarian Split Squat [25–29]; and (c) single-leg stance, as Step-Up and Down [30–33]. However, to the best of our knowledge, few studies have investigated the QF activation during lower limb strength exercises performed with bodyweight [29,34–37], despite these exercises being commonly used in rehabilitation programs and in the early stages of recovery from muscle and knee injuries [38,39]. The limited EMG data available suggest several important findings that warrant confirmation in future research: (i) bodyweight exercises that involve a greater mechanical arm or moment may lead to increased activation of the QF muscle bellies [19]; (ii) unilateral exercises (such as Bulgarian Split Squat), which require greater knee stability control, tend to activate the vasti muscles more than the rectus femoris [35]; and (iii) increasing the knee flexion/extension range of motion during Step-Down exercises may increase the QF activation levels [36]. Given these characteristics, athletes often select specific knee joint angles to optimize movement initiation, depending on the desired athletic [40–42]. However, a significant debate persists regarding whether such coordinated muscular activity stems from a common neural pathway or merely reflects the physical limitations inherent in a particular task [43,44]. Further complicating this understanding, various authors have observed differential activation patterns in the proximal and distal regions of the rectus femoris when comparing isometric knee extension and hip flexion tasks [45,46].

In addition to the limited number of studies on QF activation during bodyweight exercises, methodological differences in the use of electromyography make it difficult to compare the exercises analyzed in the different studies. In this sense, EMG is a very variable signal that largely depends on the electrode placement and subcutaneous layer thickness [47,48], exercise execution speed [49,50], signal processing (i.e., filtering, smoothing, normalization, extraction of peak or average values) [51], muscle fatigue [52], etc. Beyond these methodological constraints, the conceptual interpretation of the signal is equally critical [7]. Differences in activation across exercises hold functional relevance primarily as indicators of distinct acute neuromuscular demands rather than as direct predictors of long-term adaptations [53]. Nevertheless, the analysis of exercise-specific activation patterns can directly inform clinical and athletic decision-making by assisting practitioners in selecting tasks that reproduce the spatiotemporal and coordinative demands of functional movements [54]. This approach supports the principle of specificity and potentially enhances motor coordination and joint stability, without implying guaranteed transfer to chronic performance improvements [55]. Under this framework, further EMG studies, performed under similar methodologi-

cal conditions, are needed to better understand the differences in muscle activation between the most used bodyweight strength exercises for lower limb injury prevention and rehabilitation.

Considering the limited information on QF activation during bodyweight strength exercises, the purpose of the current study was to analyze the activation of four different QF muscle bellies during seven lower-limb exercises using bodyweight commonly utilized in injury prevention and rehabilitation programs. We hypothesized that the Russian Belt would be the exercise with the greatest overall activation of all muscle bellies of the QF since it involves a greater lever arm of the body weight to the knee, which probably contributes to greater activation.

2. Methods

2.1. Participant Characteristics

This controlled laboratory study involved 20 healthy male amateur football players (age: 28.1 ± 6.3 years; height: 173.9 ± 5.4 cm; body mass: 77.6 ± 8.5 kg) in a single-occasion repeated measures design. Eligible participants had to practice football, including physical training and drills on the pitch > 3 h per week. To be included in the procedure, participants also had to meet the following criteria: (a) be free of injuries at the time of the study, (b) have no history of lower limb (muscle or joint) injury in the six months prior to registration, and (c) be free of the presence of delayed-onset muscle soreness at the test session. Before the start of this investigation, written informed consent was obtained from all participants, and the procedures were conducted following the Declaration of Helsinki and were approved by the University Ethics Review Committee (code: DES.FJVG.JVC.24).

2.2. Procedure

All participants reported familiarity with the exercises, as they were regularly included in their strength training routines. After a brief warm-up consisting of two sets of eight submaximal knee extensor and flexor contractions at $60^\circ/\text{s}$ on an isokinetic dynamometer (Biodex System 4 Pro, Biodex Medical Systems Inc., Shirley, NY, USA), participants were instrumentalized to record surface EMG in the four bellies of QF of their dominant limb, as explained below. EMG instrumentalization was conducted to independently assess the activation of the rectus femoris proximal (RFP), rectus femoris medial (RFM), vastus lateralis (VL), and vastus medialis (VM). Participants were then seated on the isokinetic dynamometer with both the hip and knee positioned at 90° of flexion [56] and performed two 5 s maximal voluntary isometric contractions (MVICs) of QF with a 1 min rest between efforts, exerting maximal effort to extend the knee. Afterwards, they performed the exercises (Figure 1) in a randomized order while EMG data were collected at 2000 Hz. Twelve complete repetitions per exercise were performed following a cadence controlled by a metronome (set at 25 bpm), and 2 min of rest were provided between each exercise to allow recovery. The correct execution of each exercise was supervised by two researchers, who used goniometry to control and standardize participants' execution. In addition, the execution of all exercises was videotaped from a sagittal plane and revised afterwards to ensure correct execution of exercises before EMG data analysis.

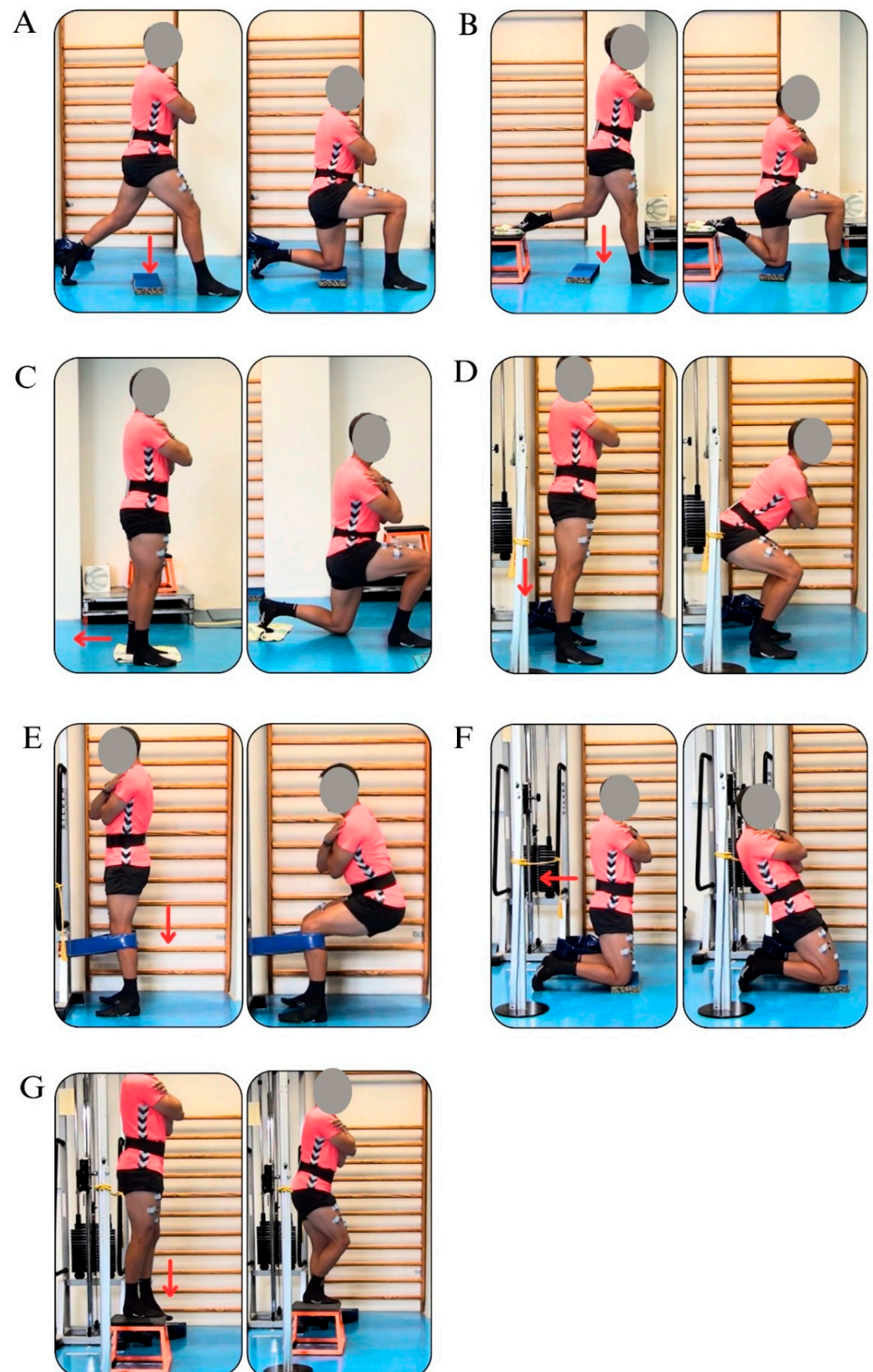


Figure 1. The seven examined exercises: (A) Split Squat, (B) Bulgarian Split Squat, (C) Backward Lunge, (D) Half-Squat, (E) Russian Belt, (F) Reverse Nordic, and (G) Lateral Step-Down. The red arrow indicates the direction of movement.

2.3. EMG Recording

A wireless EMG system with integrated inertial measurement units (Ultium EMG, Noraxon, Scottsdale, AZ, USA), featuring 24-bit A/D conversion, dynamic resolution, and a common mode rejection ratio greater than 100 dB, was used to record the electrical activity of the QF muscle at a sampling rate of 2000 Hz. Electrode positioning was performed according to SENIAM recommendations (<http://www.seniam.org>) (accessed on 8 January 2026), except for the electrodes placed in the RFP site, which were placed at one-third on the line from the anterior superior iliac spine to the superior part of the patella, as previously suggested [57]. Prior to electrode placement, the skin was shaved and cleaned with 70° alcohol, and then 24-mm diameter pre-gelled polymer Ag/AgCl coated electrodes (Kendall™, H124SG, 30 × 24 mm, Dublin, OH, USA) were placed over the muscle bellies of RFP, RFM, VL, and VM, longitudinally to the muscle fibers. Muscle bellies were identified at origin and insertion by palpation during an isometric QF contraction, and correct placement and signal quality were confirmed by asking participants to perform several interspersed contractions to visualize the recording of EMG signals. The wireless device was secured using Hypafix® adhesive tape (5 cm wide, BSN Medical, Hull, UK) to avoid any discomfort during the execution of the MVIC and the bodyweight strength exercises. Throughout the recording, the signals were transferred to a computer where they were monitored using MR.3.18 software and stored for further analysis.

2.4. Exercises

All exercises consisted of two consecutive phases: first an eccentric phase, and then a concentric phase, performed at the metronome-controlled cadence and with the arms crossed over the chest. The eccentric phases of the exercises were performed as follows (Figure 1):

2.4.1. Split Squat

The exercise began with the participant standing in a fixed position, with the dominant lower limb placed forward and the trunk maintained in a neutral posture. The participant then lowered the body until both the hip and knee of the dominant leg were flexed to 90°. At this point, the knee of the non-dominant leg was required to touch the ground to ensure proper execution (Figure 1A). From this position, the participant returned to the initial standing posture to complete the repetition and repeated the movement for up to 12 repetitions.

2.4.2. Bulgarian Split Squat

This exercise was performed in a manner similar to the Split Squat, except that the non-dominant rear foot was placed dorsally on a 30 cm-high box throughout the movement (Figure 1B).

2.4.3. Backward Lunge

The participant began in a standing position with both feet parallel and shoulder-width apart. Using a sliding mat, the non-dominant leg was extended backward while maintaining a neutral trunk posture. Simultaneously, the participant lowered the body until the hip and knee of the dominant leg—kept in a fixed, anterior position—were flexed to approximately 90°. Proper execution was ensured by having the knee of the non-dominant leg make contact with the ground at the end of the eccentric phase (Figure 1C).

2.4.4. Half-Squat

The exercise started from a standing position with feet shoulder-width apart and toes pointed forward. In this position, the participant squatted to 90° of knee flexion with the

trunk in a natural position. A horizontal rope was positioned behind the participant to provide tactile feedback, indicating the endpoint of the Squat movement (Figure 1D).

2.4.5. Russian Belt

The participant started the exercise standing with his knees fully extended. A 13 cm wide Russian Belt was secured to a wall-mounted espalier and wrapped around the tibia immediately below the knee joint. Maintaining a neutral trunk posture, the participant leaned backward during the eccentric phase, aiming to reach approximately 90° of knee flexion (Figure 1E).

2.4.6. Reverse Nordic

The participant began the exercise kneeling on a rigid foam pad with the trunk held upright. He then performed a slow, controlled backward movement toward the floor, maintaining pelvic retroversion and a straight trunk, until reaching approximately 40° of knee flexion. A horizontal rope positioned behind the participant provided feedback to indicate the endpoint of the movement (Figure 1F).

2.4.7. Lateral Step-Down

The exercise began with the participant standing on one leg, with the dominant foot positioned near the edge of a 30 cm-high box. The movement involved a controlled, unilateral lowering of the body until the dominant knee reached approximately 40° of flexion, while maintaining a neutral trunk posture. A horizontal rope was placed behind the participant to provide tactile feedback indicating the endpoint of the knee flexion (Figure 1G).

2.5. Data Reduction

All raw EMG signals were digitally filtered using a fourth-order, low-pass Butterworth filter (10–450 Hz cutoff frequency) to reduce noise, whether from other electrical sources in the human body, from external sources or the measurement process itself. Secondly, full-wave rectification and low-pass filtering at 8 Hz was applied using a second-order, zero-offset Butterworth filter. For each muscle, a moving average EMG signal (500 ms time constant) was used to identify the peak EMG signal within each exercise repetition. The peak EMG for each exercise was calculated using the mean of the peak EMG of the four central repetitions of the 12 executed considering the entire movement cycle, including both concentric and eccentric phases. The mean peak amplitude of the EMG signal for each exercise was normalized to the highest peak amplitude recorded across the two MVIC trials (% MVIC).

2.6. Statistical Analysis

The EMG activity of each muscle belly during the MVICs and the different exercises was analyzed by using the SPSS statistical package (v27.0.1, SPSS Inc, Chicago, IL, USA). A 1-way repeated measures ANOVA with the within-subject factor “bodyweight exercises” was calculated to search for differences between exercises in each muscle belly. A 1-way repeated measures ANOVA with the within-subject factor “muscle belly” was calculated to search for differences between muscles within each exercise. When a significant F-value was reached, post-hoc pairwise comparisons were made with the Bonferroni adjustment. Significance for statistical analysis was set at a level of $p < 0.050$. The reliability of the normalized peak EMG amplitudes was tested in a previous pilot study ($n = 5$) with two sets of 12 repetitions per exercise using the intraclass correlation coefficient (ICC) and the standard error of measurement (SEM). The ICC was calculated with the respective

95% confidence interval (CI), and ICC values were interpreted as poor (<0.50), moderate ($0.50\text{--}0.75$), good ($0.76\text{--}0.90$), and excellent (>0.9) [58].

3. Results

For most exercises, good to excellent ICC values were found between sets for all QF bellies ($0.80 < \text{ICC} < 0.99$) with SEM values lower than 20%. Only Backward Lunge in RFP and Reverse Nordic in VL showed moderate ICC values (0.70 and 0.61, respectively) (Table S1).

As shown in Table 1, the highest mean peak EMG amplitudes of VM and VL were found in Bulgarian Split Squat (VM: $85.4 \pm 31.8\%$ MVIC; VL: $67.6 \pm 22.2\%$ MVIC) and Backward Lunge (VM: $74.5 \pm 23.5\%$ MVIC; VL: $59.9 \pm 16.6\%$ MVIC), while the lowest were found in Reverse Nordic (VM: $47.3 \pm 17.8\%$ MVIC; VL: $42.2 \pm 15.2\%$ MVIC) and Half-Squat (VM: $47.5 \pm 17.4\%$ MVIC; VL: $41.3 \pm 13.9\%$ MVIC). For rectus femoris, the highest EMG amplitudes were found in Russian Belt (RFP: $49.8 \pm 27.4\%$ MVIC; RFM: $39.6 \pm 19.9\%$ MVIC) and Backward Lunge (RFP: $40.4 \pm 21.6\%$ MVIC; RFM: $31.4 \pm 17.1\%$ MVIC), and the lowest in Split Squat (RFP: $25.0 \pm 14.2\%$ MVIC; RFM: $16.6 \pm 10.0\%$ MVIC), Half-Squat (RFP: $27.2 \pm 12.3\%$ MVIC), and Reverse Nordic (RFM: $17.8 \pm 10.5\%$ MVIC). Regarding the comparison between muscles, significant differences in the mean peak EMG amplitudes were obtained in all exercises evaluated (Table 1). EMG amplitudes of VM and VL were significantly higher ($p < 0.050$) compared to RFP and RFM in most exercises, except for the comparison between the vasti muscles and RFP in the Russian Belt (VM-RFP: $p = 0.270$; VL-RFP: $p = 0.633$), and between VL and RFP in the Reverse Nordic ($p = 0.077$). On the other hand, although VM and RFP activation tended to be greater than VL and RFM activation, respectively, the pairwise comparisons showed that there were only significant differences ($p = 0.004$) between VM and VL in Split Squat (VM $>$ VL), and no significant differences between RFP and RFM in any exercise.

Regarding the EMG comparison between exercises, the ANOVA found significant differences for VM ($F = 7.22$, $p < 0.001$), VL ($F = 6.74$, $p < 0.001$), RFM ($F = 5.75$, $p < 0.001$), and RFP ($F = 3.28$, $p < 0.005$). Figure 2 shows the pairwise comparisons, ranking the exercises from the lowest to the highest mean peak EMG amplitudes for each muscle belly. For RFP, Russian Belt produced the highest activation levels, being significantly different from Half-Squat ($p = 0.015$) and Split Squat ($p = 0.005$), which obtained the lowest activation levels. For RFM, Russian Belt obtained higher activation levels than Half-Squat ($p = 0.006$), Lateral Step-Down ($p = 0.006$), and Reverse Nordic and Split Squat ($p < 0.001$); furthermore, Backward Lunge showed greater activation levels than Split Squat ($p = 0.043$). For VL, Bulgarian Split Squat generated higher activation levels compared to Split Squat ($p = 0.002$), Reverse Nordic and Half-Squat ($p < 0.001$). Backward Lunge showed greater activation levels than Reverse Nordic ($p = 0.022$) and Half-Squat ($p = 0.014$), and Russian Belt obtained higher activation levels compared to Half-Squat ($p = 0.035$). Finally, for VM, Bulgarian Split Squat produced higher activation levels than Split Squat ($p = 0.035$), Russian Belt ($p = 0.033$), Lateral Step-Down ($p = 0.030$), Half-Squat ($p < 0.001$), and Reverse Nordic ($p < 0.001$). In addition, Backward Lunge showed greater activation levels ($p < 0.005$) than Half-Squat and Reverse Nordic.

Table 1. Mean peak EMG amplitudes (% MVIC) of the four quadriceps femoris bellies during various bodyweight strength exercises.

Exercises	Quadriceps Femoris				Between Muscle Comparison		
	RFP (Mean ± SD)	RFM (Mean ± SD)	VL (Mean ± SD)	VM (Mean ± SD)	F	<i>p</i>	Post-Hoc
Split Squat	25.0 ± 14.2	16.6 ± 10.0	46.2 ± 12.4	63.0 ± 20.5	39.42	<0.001	VM > VL > RFP, RFM
Bulgarian Split Squat	33.9 ± 20.0	27.0 ± 17.4	67.6 ± 22.2	85.4 ± 31.8	27.19	<0.001	VM = VL > RFP, RFM
Backward Lunge	40.4 ± 21.6	31.4 ± 17.1	59.9 ± 16.6	74.5 ± 23.5	18.11	<0.001	VM = VL > RFP, RFM
Half-Squat	27.2 ± 12.3	21.9 ± 13.9	41.3 ± 13.9	47.5 ± 17.4	13.19	<0.001	VM = VL > RFP, RFM
Russian Belt	49.8 ± 27.4	39.6 ± 19.9	58.2 ± 19.6	62.8 ± 20.5	4.23	0.008	VM = VL > RFM
Reverse Nordic	30.1 ± 17.5	17.8 ± 10.5	42.2 ± 15.2	47.3 ± 17.8	14.24	<0.001	VM > RFP, RFM/VL > RFM
Lateral Step-Down	34.0 ± 25.4	21.9 ± 14.8	54.9 ± 17.6	62.6 ± 20.4	17.41	<0.001	VM = VL > RFP, RFM

Data are presented as mean ± SD for 20 participants. Mean peak EMG amplitudes were normalized to values obtained during a quadriceps maximal voluntary isometric contraction (MVIC) performed on an isokinetic dynamometer. Abbreviations: MVIC, maximal voluntary isometric contraction; RFP, rectus femoris proximal; RFM, rectus femoris medial; VL, vastus lateralis; VM, vastus medialis. Results of the statistical comparison between muscle bellies are shown in the post hoc comparisons (“>” indicates significantly higher than, “=” indicates non-significant differences at $p < 0.050$).

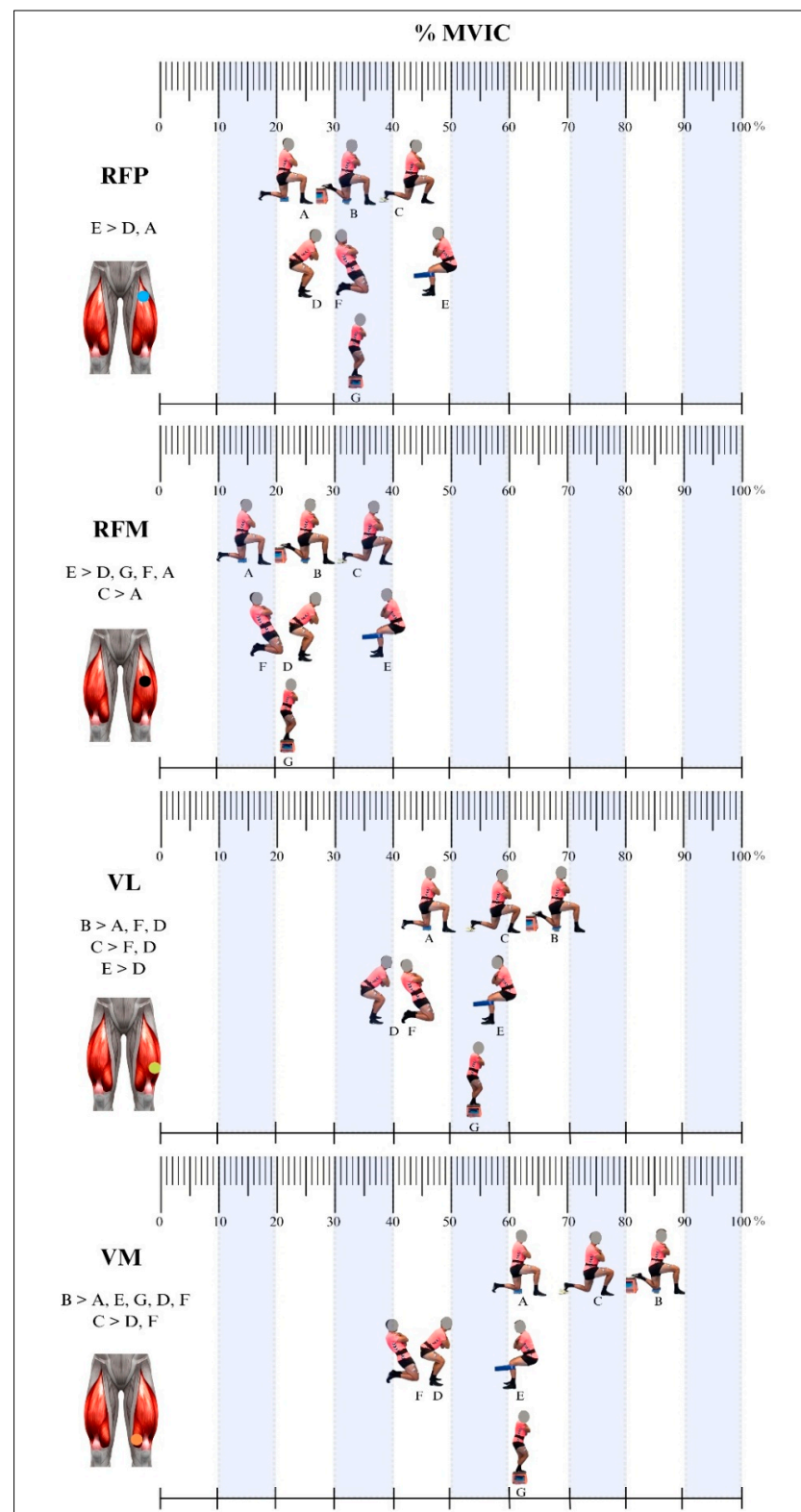


Figure 2. Comparison between exercises for the normalized mean peak EMG amplitudes of rectus femoris proximal (RFP), rectus femoris medial (RFM), vastus lateralis (VL), and vastus medialis (VM). For each muscle belly, the seven exercises were placed along a scale [ranging between 0 and 100% of maximal voluntary isometric contraction (% MVIC)] to rank the exercises based on the muscle activation. Lower limb exercises: (A) Split Squat, (B) Bulgarian Split Squat, (C) Backward Lunge, (D) Half-Squat, (E) Russian Belt, (F) Reverse Nordic, (G) Lateral Step-Down. The colored dots indicate the electrode placement according to the specific muscle analyzed. Results of the statical comparison between exercises: ">" indicates significantly higher activation than the following exercises at $p < 0.050$.

4. Discussion

To our best knowledge, there are numerous lower limb studies that categorize the activation levels of the QF bellies when executing different exercises. However, the comparison of the activation in several bodyweight strength exercises with different stances (staggered, parallel, and single-leg) is a novelty of the present investigation. In addition, a pilot study was performed to assess the consistency of the EMG data, finding acceptable levels of reliability, especially for the ICC results (with values ≥ 0.80 for most exercises and muscles), which is in line with previous data [29].

According to the criteria used in prior EMG studies to categorize levels of muscle activation for lower limb strength exercises [33,37], VM and VL showed high to very high normalized EMG amplitudes in all exercises analyzed, while RFM and RFP showed low to moderate EMG values. Interestingly, unlike the vasti muscles, RFP only obtained EMG values above 40% (threshold that has been referred to as necessary to reach for increasing muscle strength with resistance training) [59,60] for Russian Belt and Backward Lunge, and RFM did not show EMG values higher than this theoretical threshold. Previous studies found that the Lateral Step-Down [33], the Half-Squat [35], and the Bulgarian Split Squat [37] obtained EMG amplitudes with respect to those of an MVIC similar to the ones reported here, suggesting that these exercises do not produce enough activation to induce improvements in muscle strength, particularly in trained individuals. However, these bodyweight exercises, even those who obtained low to moderate activation values, could be useful for patients with patellofemoral pain syndrome [38], knee osteoarthritis [39], or in the early stages of recovery from knee and muscle injuries. Although the EMG studies have provided insight into the neuromuscular system and how different exercises might impact muscle excitation, it is currently unclear whether higher muscle excitation, as determined by EMG, is indicative of long-term adaptation [61]. While these thresholds provide a traditional benchmark for exercise intensity, they must be interpreted with caution under modern neurophysiological frameworks. While these thresholds provide a traditional benchmark for exercise intensity, they must be interpreted with caution under modern neurophysiological frameworks. In this regard, the amplitude of the signal should be interpreted strictly as an index of acute muscle excitation, reflecting sarcolemmal depolarization and neural strategies—such as motor unit recruitment patterns and discharge behavior—that characterize immediate motor control and efficiency [54]. While these variations may precede subsequent structural changes, EMG should not be viewed as a direct measure of force production or a deterministic predictor of long-term neuromuscular adaptation [62]. Although EMG signal magnitude is frequently used in clinical and athletic settings to inform training decisions, its interpretation as a surrogate marker of hypertrophy or strength gains must be approached with caution; current evidence does not provide definitive longitudinal support for the notion that greater acute activation necessarily translates into superior chronic outcomes [7]. Within this framework, the differences observed in EMG activity across exercises—such as the high activation found in the Russian Belt or Bulgarian Split Squat—are more plausibly indicative of distinct acute neuromuscular demands that, according to computational models [53], may enhance stretch-shortening cycle efficiency and motor unit synchronization, without implying a guaranteed transfer to chronic structural performance improvements.

Regarding the differences in activation between the different QF muscle bellies, the normalized EMG amplitudes of VM and VL were significantly higher than those of RFP and RFM in most exercises, which is in line with previous studies on Bulgarian Split Squat [29,34], Half-Squat [12,63,64], and Lateral Step-Down [36]. These differences were mainly observed in the exercises performed in staggered stance and single-leg stance, that is, unilateral exercises that require great control of body stability, in which VM and VL may

play a fundamental role in the lateral stabilization of the patella [65]. However, differences between vasti muscles and rectus femoris do not seem to be attributed exclusively to the stabilizing role of the vasti muscles, as similar differences (although not always significant) were also found in exercises performed in a parallel stance. Possibly, the differences in the normalized EMG amplitudes between the QF muscle bellies could also be influenced by the technique used to achieve the MVIC. This technique, although it is the most used in QF EMG studies [21,24,30,66], could have favored the achievement of maximum activation for RFP and RFM, but not for VM and VL, as these latter muscle bellies have a more oblique orientation. If this had been the case, the normalization process of the VM and VL EMG signals (with respect to supposedly non-maximum values) would have resulted in an overestimation of their activation level during the bodyweight strength exercises. To avoid this potential problem, it might have been appropriate to perform different MVIC techniques to ensure the achievement of actual maximum values. This current study limitation is common to most QF EMG studies in the literature, which typically use a single MVIC technique to normalize the EMG, usually the 90° degree knee and hip flexion position [21,24,30,66]. Other studies have used other positions, such as 70–75° of knee flexion [67,68], 60° of knee flexion [10,27,69], and even supine positions [37], but there is no adequate knowledge about which positions are most suitable for each of the QF muscle bellies, so further research is needed to overcome this limitation.

Concerning the comparison between exercises, Figure 2 shows the exercise ranking from the lowest to the highest level of activation for each muscle belly, which may be useful for exercise professionals when making decisions about the progression of bodyweight strength exercise programs. In general, the Russian Belt, Bulgarian Split Squat, and Backward Lunge were the exercises that produced the highest levels of QF activation. For the rectus femoris, the Russian Belt showed higher EMG levels than Split Squat and Half-Squat in RFP and RFM [19], in addition to Lateral Step-Down and Reverse Nordic in RFM. These differences could be due to the greater lever arm of the body weight to the knee in the Russian Belt (exercise that involves a large posterior displacement of the center of mass) and the smaller range of knee motion in the Lateral Step-Down and Reverse Nordic (40° of knee flexion compared to 90° in the Russian Belt), which reduced the speed of these exercises, as all exercises analyzed in this study were performed at the same cadence. For the vasti muscles, the Bulgarian Split Squat and Backward Lunge produced higher levels of activation than Split Squat, Reverse Nordic, and Half-Squat in VL, and also than Russian Belt and Lateral Step-Down for VM, which agrees with other studies that compared Bulgarian Split Squat and Split Squat [70]. Possibly, the placement of the non-dominant rear foot resting on its dorsal side on a box during the Bulgarian Split Squat and the sliding back of the non-dominant limb during the Backward Lunge, posed a significant challenge to postural control and required high levels of vasti muscle activation to control knee stability during knee flexion. On the other hand, although the unilateral lowering of the body during the Lateral Step-Down may also suppose a great challenge of body postural control and knee stability, the range of knee motion in this exercise was short (40°) in comparison to the Bulgarian Split Squat and Backward Lunge (90°), which reduced this exercise difficulty and, as a result, the QF activation level. In this context, other studies that assessed the Lateral Step-Down at 60° of knee flexion [35], as well as a study comparing a full Step-Down with a half Step-Down [36], reported higher quadriceps femoris activation along with increased biomechanical demands on the knee and hip.

This study has several limitations that should be acknowledged. First, the use of a single MVIC method for EMG normalization may have influenced comparisons between muscle bellies. Second, performing 12 repetitions per exercise could have induced muscle fatigue; however, a 2 min rest was provided between trials, and the exercises were con-

ducted in a counterbalanced order to minimize this effect. Third, the study population was limited to healthy, male amateur football players. Therefore, these findings may not be directly generalizable to other cohorts, such as female athletes, sedentary individuals, or populations in different age groups, whose neuromuscular recruitment strategies may differ.

5. Conclusions

Most bodyweight strength exercises produced higher levels of muscle activation in VM and VL compared to RFP and RFM. The exercises were ranked based on the level of activation for each muscle belly, with the Bulgarian Split Squat and Backward Lunge (the exercises with greatest demands of knee stability) generating the highest levels of VM and VL activation, and the Russian Belt (the exercise with a greatest lever arm of the body weight to the knee) showing the highest activation levels for RFP and RFM. These findings inform exercise selection and progression based on specific acute neuromuscular demands and coordinative challenges, rather than serving as long-term structural predictions. By identifying the unique activation patterns of each task, practitioners can design quadriceps femoris prevention and rehabilitation programs, ensuring a progression that respects the principle of specificity without implying a deterministic relationship with chronic adaptations.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16041940/s1>, Table S1: Reliability based on mean peak EMG amplitudes (%MVIC) for each bodyweight strength exercise obtained in a previous pilot study ($n = 5$).

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