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Original Article

Evaluation of Muscle Activation and Ground Reaction Forces in Lunge Exercises with and Without Resistance Band Assistance

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What is already known on this topic?

- *The forward lunge is a closed kinetic chain exercise widely used in training and rehabilitation to improve lower-extremity muscle strength, stability, and functional performance.*
- *Previous studies have investigated the effects of different forward lunge variations, including forward, lateral, backward, step-based, and resistance-based variations, on muscle activation and ground reaction forces; however, most studies have focused on either electromyographic activity or mechanical loading parameters separately.*
- *Elastic resistance bands and variations in step height are used to manipulate exercise intensity and mechanical demand, yet their effects on large lower-extremity muscle groups remain insufficiently investigated. Current evidence also suggests that ground reaction forces may be more sensitive to loading conditions such as step height and movement strategy than muscle activation.*

Abstract

The aim of this study was to compare muscle activation and ground reaction forces in four different forward lunge variations performed with and without resistance band assistance. The study included 21 male athletes (age: 21.28 ± 1.84 years, height: 176.86 ± 4.00 cm, body weight: 72.59 ± 9.17 kg, sporting experience: 9.47 ± 2.48 years, body mass index: 23.18 ± 2.49 kg/m^2). Participants performed the following exercises in sequence: forward lunge on flat ground (0 cm), forward lunge from a height of 15 cm, forward lunge on flat ground (0 cm) + resistance band assistance, and forward lunge from a height of 15 cm + resistance band assistance. During four different forward lunge exercises, muscle activations of the biceps femoris, vastus medialis, rectus femoris, and vastus lateralis were recorded using surface electromyography, while ground reaction forces were simultaneously measured using a force platform. The forward lunge step exercises were performed with the knee angle at 90°, three times with the right foot and three times with the left foot. Significant increases in ground reaction forces were observed, particularly in the 15 cm high forward lunge exercise ($p < .05$). In contrast, no significant difference was found in muscle activation ($p > .05$). Although different forward lunge variations did not significantly affect muscle activation, it was determined that forward lunge applications performed from a height of 15 cm significantly increased ground reaction force. In conclusion, muscle activation was only minimally affected by the variations, whereas the mechanical loading pattern was found to be decisive for ground reaction force. For strength and power development, forward lunge variations involving forward falls from height can be recommended; for stabilization and movement control, resistance band-assisted forward lunge step variations can be recommended.

Keywords: Electromyography, ground reaction force, lunge step, muscle activation, resistance band

Introduction

The forward lunge (FL) movement is one of the primary exercises used to improve lower extremity strength, stability, and functional performance. Functional performance, in this context, refers to the ability to effectively perform sport-specific movements and activities of daily living that require coordinated lower extremity force production and balance (Behm & Anderson, 2006). The lunge step is frequently preferred in both sports performance development and rehabilitation settings because it involves mechanical characteristics similar to those of daily life activities (e.g., walking and stair climbing). This exercise requires coordinated muscle activation and efficient load transfer across the hip, knee, and ankle joints (Riemann et al., 2013; Jönhagen et al., 2009).

The FL is considered a functional, multi-joint exercise that activates multiple muscle groups simultaneously rather than isolating a single muscle. Previous studies have reported increased activation of the gluteus maximus, vastus medialis (VM), and hamstring muscles during FL movements (Ekstrom et al., 2007; Boudreau et al., 2009). Furthermore, different FL variations (e.g., forward, lateral, backward, step based, and resistance based) have been examined in relation to muscle activation and ground reaction force (GRF). However, most of these studies have focused either on electromyography (EMG) activity or on mechanical loading parameters alone, rather than examining both simultaneously.

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What this study adds to this topic?

- *This study simultaneously compares forward lunge variations performed with and without resistance band assistance on a flat surface (0 cm) and from a 15-cm height.*
- *The findings demonstrate that muscle activation remained relatively similar across conditions, whereas ground reaction forces increased significantly, particularly during the 15-cm height conditions, highlighting a dissociation between neuromuscular activation and mechanical loading.*
- *These findings provide practical guidance for exercise prescription, suggesting that 15-cm height forward lunge variations may be useful for strength and power development, whereas resistance band-assisted variations may be more appropriate for stabilization, coordination, and movement control.*

Resistance training is typically performed using external loads such as free weights or exercise machines. However, because many sports involve unilateral movement patterns, exercises such as the lunge are particularly important for enhancing single-leg performance (Ekstrom et al., 2007). Unilateral exercises are also known to play a key role in addressing inter-limb asymmetries and improving neuromuscular coordination (McCurdy et al., 2005; Bettariga et al., 2022). In practical settings, lunge exercises are performed using various techniques, including stepping, jumping, and, more recently, stepping or dropping from different heights.

Elastic resistance bands have increasingly been incorporated into these applications. Their primary characteristic is that resistance increases progressively with elongation. Because of their low cost, portability, and versatility, they are widely used by coaches and practitioners. Resistance bands and variations in step height are commonly applied to manipulate exercise intensity and mechanical demand (Andersen et al., 2008; Aboodarda et al., 2016). Despite their widespread use, the effects of elastic resistance bands on large lower extremity muscle groups remain insufficiently explored. While previous research has demonstrated their effectiveness in strengthening smaller muscle groups, such as those in the upper body, their influence on larger and stronger lower extremity muscles has not yet been comprehensively investigated (Andersen et al., 2011; Seguin et al., 2022; Andersen et al., 2010).

Various FL step variations have long been used by coaches and athletes, particularly in athletics and field-based sports. These exercises are considered demanding and are thought to enhance eccentric strength, particularly in the hamstring muscle group (Jönhagen et al., 2009). Unlike isolated exercises performed on isokinetic dynamometers, such as knee flexion-extension, the FL is a closed kinetic chain movement that more closely reflects functional activity (Pincivero et al., 2000). Additionally, FL exercises have been used to identify movement pattern differences in rehabilitation contexts (Alkjaer et al., 2002; Mattacola et al., 2004). However, despite their widespread use, the neuromuscular and mechanical responses associated with transitions between different loading conditions remain insufficiently understood.

Electromyography is widely used to assess muscle activation levels during rehabilitation and strength training exercises (Andersen et al., 2006). Electromyography provides insight into neuromuscular activation patterns and allows for the quantification of muscle recruitment during dynamic movements. The EMG signal reflects the sum of motor unit action potentials and is typically normalized to maximum voluntary isometric contraction (MVIC) values. This normalization enables the expression of muscle activity as a percentage of maximal activation and facilitates comparisons between individuals and conditions (Ballantyne et al., 1993; Hintermeister et al., 1998).

Although EMG and GRF are frequently examined independently in the literature, they represent different but complementary aspects of human movement. The EMG reflects the neural drive to the muscles, whereas GRF reflects the external mechanical outcome of this activation. However, the relationship between EMG amplitude and force production is not always linear, particularly in multi-joint functional movements. This is influenced by factors such as motor unit recruitment strategies, intermuscular coordination, and the contribution of passive elastic components within the muscle–tendon unit (Vigotsky et al., 2022; Hug et al., 2015). Therefore, similar EMG activation levels may produce different mechanical outputs depending on task conditions. Understanding this dissociation is essential for accurately interpreting the effectiveness of different exercise variations in both training and rehabilitation contexts (Balshaw et al., 2022).

In contrast, the GRF represents the mechanical output of movement and reflects the interaction between the body and the ground. While EMG provides information about neuromuscular activation, GRF reflects the external loading demands imposed on the musculoskeletal system. Therefore, evaluating both EMG and GRF simultaneously provides a more comprehensive understanding of movement mechanics.

Current evidence suggests that variations in loading conditions and posture may have limited effects on muscle activation, whereas GRF appears to be more sensitive to factors such as step height, movement velocity, and task execution strategy. Accordingly, the standard FL exercise has been shown to produce low to moderate EMG activation levels in the hip and thigh musculature (Boudreau et al., 2009; Ekstrom et al., 2007). Farrokhi et al. (2008) demonstrated that a forward-leaning trunk position significantly increased EMG activation of the gluteus maximus and biceps femoris (BF) compared to an upright posture, although no significant difference was observed for the vastus lateralis (VL) muscle.

Although the effects of FL variations on muscle activation and GRF have been investigated in previous studies (Boudreau et al., 2009; Ekstrom et al., 2007), research examining combined conditions—such

as resistance band-assisted FLs and FLs performed from an elevated height—remains limited. Furthermore, studies simultaneously evaluating both EMG and GRF variables are relatively scarce (Günay & Gülmez, 2023).

Therefore, this study aims to compare muscle activation and GRFs across four different FL step variations performed with and without resistance band assistance, both on a flat surface (0 cm) and from a height of 15 cm. It is hypothesized that increasing mechanical demand, particularly through forward stepping from a height, will result in significant increases in GRFs, whereas muscle activation levels will exhibit relatively limited variation.

In this context, the present study also seeks to contribute to the existing literature by examining whether neuromuscular activation and mechanical loading responses can be considered partially independent variables during functional lower extremity exercises.

Despite the growing body of literature on lunge exercises, there remains a lack of comprehensive studies investigating the combined effects of external loading variations, such as elastic resistance and drop height, on both neuromuscular and mechanical responses. Previous studies have generally focused on isolated variables, limiting the understanding of how combined loading strategies influence movement mechanics and muscle activation patterns (Dos'Santos 2020). In particular, the interaction between increased mechanical demand (e.g., forward stepping from an elevated surface) and assisted resistance conditions has not been sufficiently explored. This gap restricts the ability to fully interpret how different lunge variations affect performance outcomes, neuromuscular control, and mechanical loading strategies.

From a practical perspective, the findings of this study may provide valuable insights for exercise prescriptions. Exercises involving forward stepping from a height may be more suitable for strength and power development, whereas resistance band-assisted variations may be more appropriate for stabilization and movement control training programs.

Material and Methods

Research Group

The population of this study consists of male athletes aged 18–25. The sample group of the study comprises 21 athletes with an average age of 21.28-± 1.84 years, an average height of 176.86 ± 0.4 cm, an average body weight of 72.59 ± 9.17 kg, 9.47 ± 2.48 years of sporting experience, and a body mass index (BMI) of 23.18 ± 2.49 (kg/m^2).

Table 1.
Descriptive Statistics of the Demographic Characteristics of the Athletes Participating in the Study

	N	$\bar{X}$	SD	Min.	Max.
Age	21	21.28	1.84	19	26
Height (cm)	21	176.86	4.00	171	186
Body weight (kg)	21	72.59	9.17	55.30	94.50
Sports age (years)	21	9.47	2.48	4	14
BMI	21	23.18	2.49	17.65	27.75

BMI, body mass index; cm, centimeter; kg, kilogram; Max, maximum; Min, minimum; N, sample size; SD, standard deviation; $\bar{X}$, mean.

The participants were actively engaged in different sports disciplines, including athletics, cycling, judo, karate, American football, volleyball, soccer, and tennis. The sample size was calculated using G*Power (version 3.1.9.2, Düsseldorf, Germany). A priori power analysis was conducted based on a repeated measures ANOVA (within-subject design) to compare four different lunge conditions. The significance level (α) was set at 0.05, statistical power ($1-\beta$) at 0.80, and the effect size (ES) at 0.6 (medium effect) (Cohen, 1988). The minimum required sample size was calculated as 19 participants; therefore, the inclusion of 21 participants was considered sufficient. The anthropometric measurements of the athletes are presented in Table 1. It was verified that licensed athletes had passed the necessary health checks to obtain their licenses, and after confirming that these health check documents and licenses were still active, they were allowed to participate in the tests. This study was approved by the Clinical Research Ethics Committee of Marmara University Faculty of Medicine (Protocol No.: 09.2022.824; Date: May 6, 2022) Furthermore, this study was conducted in accordance with the Helsinki Declaration. Before starting the study, participants were given an informed consent form explaining the purpose and content of the study and were asked to sign a form indicating their voluntary participation. Data collection, including the familiarization period and experimental measurements, was conducted between October 27, 2023, and January 12, 2024.

Study Method

This study was designed as a repeated-measures experimental study. Participants were called individually on the scheduled days and times, and anthropometric measurements (height, body weight) were taken. Participants' heights were measured using a Holtain (UK) stadiometer with an accuracy of 0.01 m. Participants then warmed up for 5 minutes on an Ergoline GmbH bicycle ergometer at a pedal speed of 50–60 rpm (Fradkin et al., 2010; Moritani et al., 1993; Padulo et al., 2013). After the warm-up, participants were asked to perform a lunge step exercise to ensure they could perform the movement correctly during the test. Skin and hair were cleaned to prepare participants for measurement. Electrodes were placed on the specified muscles according to the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) protocol and the experimental setup is presented in Figure 2. Electrode placement procedures were performed in accordance with SENIAM recommendations (Hermens et al., 2000), and slight adjustments were made to ensure optimal signal quality. Prior to the test, a 5-second baseline recording was performed to assess signal noise and to calibrate the force platform (Kistler, Switzerland). The EMG signals were recorded at a sampling frequency of 2000 Hz using a multi-channel system. This sampling frequency was selected to ensure accurate representation of the EMG signal. According to the Nyquist Theorem, the sampling rate should be at least twice the highest frequency component of the signal. Since surface EMG signals typically range between 20–450 Hz, a sampling rate of 2000 Hz was considered sufficient to prevent aliasing and preserve signal integrity (De Luca, 1997). Maximum voluntary isometric contraction measurements were performed for the anterior and posterior leg muscles in a seated position. During MVIC measurements, participants were seated with slight knee flexion and a stable trunk position in accordance with standard EMG testing procedures. Care was taken to maintain the torso in an upright position so that the athletes could perform the movement with the correct technique. Stride length was standardized by adjusting the distance between the force platform and the starting platform forwards and backwards to account for individual leg length differences. Participants were instructed to step forward in a controlled manner at the target angle, and EMG data was recorded during this movement.

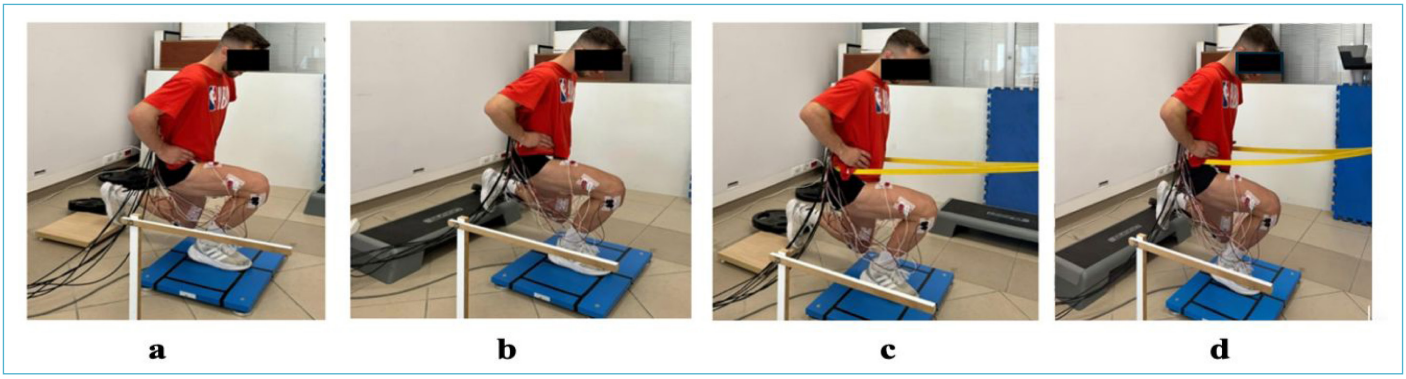

Figure 1.
Forward Lunge Exercise Conditions According to Height. (a) Flat ground (0 cm); (b) forward lunge from a 15-cm height; (c) forward lunge with elastic band assistance on flat ground (0 cm); (d) forward lunge with elastic band assistance from a 15-cm height.

Each athlete performed the movement in three repetitions; one repetition consisted of a 1-second descent onto the platform, a 1-second pause on the platform, and a 1-second return, totaling 3 seconds. A 3-second rest interval was provided between repetitions, and all durations were controlled using a metronome. First, the FL step exercise was performed on flat ground (0 cm). Then, the FL step exercise was performed with a 15 cm drop. All participants were first tested on their dominant limb, followed by the non-dominant limb, to ensure consistency in measurement order. One end of the elastic band was attached to a fixed device with a non-elastic strap. The other end was attached around the waist so that it would reach the participant's anterior sacroiliac joint. The resistance band was stretched to 50 cm, and then the FL exercise was performed first on flat ground (0 cm) and then from a height of 15 cm. Participants performed all Fl step exercises with 3 right feet and 3 left feet. During the exercise, the torso and knee angle were maintained at 90° (Figure 1). A yellow resistance band (Corength brand) was preferred to ensure the appropriate tension of the resistance band. In preliminary tests conducted with bands of different resistance levels, this band produced a level of resistance that provided sufficient tension for the participants during the FL step without compromising the correct movement form. The tension distances of the band were determined using a guide string before each test. To determine the load ratio of the band at different distances (cm) for use in measuring the assisted band FL step, the length of the band in its natural, unstretched state was determined to be 107 cm. The assisted band was attached to a fixed rig with a non-elastic string. The other end of the assisted band was pulled/stretched 50 cm with a fixed digital dynamometer to determine the kilogram measurement. The tension of the elastic band was measured using a digital hand dynamometer and expressed in kilograms-force (kgf). Accordingly, when the elastic band was stretched 50 cm (107 cm + 50 cm = 157 cm), it was determined to be 23 kg. This value corresponds to approximately 225.5 Newtons (N), providing a standardized external load across participants. It was observed that this elastic band tension was repeatable, standardizable, and did not interfere with the natural flow of movement in all participants. The elastic band was attached to a fixed apparatus with a non-elastic strap. The other end of the elastic band was attached around the participant's waist, positioned over the anterior sacroiliac joint. The tests were then conducted.

Anthropometric Measurements

Participants' heights were measured using a Holtain (UK) height scale with 0.01 cm precision. During height measurements, participants were positioned standing upright with their feet flat and barefoot, heels together, shoulders, back, and hips touching the wall (Schaafsma et al., 2013). Participants' body weights were measured in kilograms using a Tanita SC 330 (Japan) scale with a measurement accuracy of 0.1 kg. Participants' body weights were measured without shoes and wearing only shorts and a T-shirt, in a manner that would not affect their weight. Subsequently, participants' height, age, gender, and whether they were athletes or sedentary individuals were entered into the device. Then, during the measurement, the device analyzed the areas of the body through which electrons passed as they were transmitted from one foot sole and returned through the other foot sole. The resistance encountered during the transmission of electrical charges to the body during measurement varies in direct proportion to the body fat percentage. The device first determines body weight, then body fat percentage and body muscle percentage in kilograms (Yaşar & Sağır, 2021).

Placement of Electromyography Electrodes on the Designated Muscles

Electrodes were placed on the participants' specified BF, VM, rectus femoris (RF), and VL muscles according to the SENIAM protocol. Placement of electrodes on the BF muscle: To measure the activation of the BF muscle, surface EMG (sEMG) electrodes were placed on the lateral surface of the thigh, parallel to the muscle fibers, in the area corresponding to two-thirds of the distance between the greater trochanter and the back of the knee. In this study, to ensure accurate and reliable measurement of BF muscle activation, the electrodes were positioned in the relevant area, aligned with the muscle fibers and based on the specified anatomical reference points. Electrode placement on the VM muscle: In accordance with SENIAM recommendations, participants were positioned sitting on a table with the knees in slight flexion and the trunk slightly reclined during electrode placement procedures to ensure standardization and consistency. In this position, the distance between the medial upper edge of the patella and the anterior superior iliac spine (ASIS) was measured, and the point corresponding to 80% of this distance was marked. The electrode was placed on the front and medial part of the thigh, parallel to the direction of the VM muscle fibers, at this marked point. Placement of electrodes on the RF muscle; Participants were positioned sitting on a table with their knees hanging freely. In this position, the linear distance between the ASIS and the superior edge of the patella was measured, and the midpoint of this distance was marked. The electrode was placed at this marked point, parallel to the direction of the RF muscle fibers. Placement of electrodes on the VL muscle: Participants were seated on the table with their feet hanging freely. The distance between the ASIS and the lateral edge of the patella was

measured, and the 66% (2/3) point of this distance was marked. The participant was then asked to extend the relevant leg, and the most prominent (bulging) point of the VL muscle on the lateral surface of the thigh was identified. The electrodes were placed at this identified point, parallel to the direction of the muscle fibers.

Surface Electromyography Measurements

Surface EMG measurements of the participants were performed using a Biopac mp150 system EMG device. The EMG signals were sampled at a frequency of 2000 Hz using an 8-channel data acquisition system (Biopac MP150, USA). The system enabled simultaneous recording from multiple muscle groups with high temporal resolution and signal fidelity, which is essential for accurately capturing dynamic neuromuscular activity during functional movements. Studies have been conducted using this model of EMG device (Martin & Nelson, 2011). The tests to be administered to the participants were explained verbally and demonstrated as examples. Electrodes were placed on the participants' designated BF, VL, RF, and VM muscle groups. First, a FL exercise was performed on a flat surface (0 cm). Then, a FL exercise was performed after dropping from a height of 15 cm. Next, the resistance band was stretched to 50 cm and the Fl step exercise was performed on a flat surface (0 cm). Finally, the FL exercise was performed from a 15 cm drop height while the band was stretched to 50 cm. Participants performed all movements with a 90° knee angle, 3 times with the right foot and 3 times with the left foot, and the data were recorded.

Maximum Voluntary Isometric ContractionMeasurement

To determine the participants' MVIC values, measurements were taken in two different ways for the front leg muscles and the back leg muscles. To measure the VL, RF, and VM muscles, participants were asked to sit on a chair, fix their leg at 100°, and perform a knee extension movement with maximum force. Participants were verbally motivated throughout the test. Three application measurements were performed after a trial test. The highest value from the three tests was recorded, and a 2-minute rest period was given between tests.

For BF muscle MVIC measurements, participants were asked to lie face down on a stretcher. The knee joint was fixed at a 45° angle to a fixed apparatus. The participant was asked to perform a flexion movement with maximum force. Participants were motivated verbally during the test. Three application measurements were performed after a trial test. The highest value was recorded as a result of the three tests, and a 2-minute rest period was given between tests. (Suydam et al., 2017).

Analysis of Electromyography and Ground Reaction Force Data

In data analysis, raw EMG signals were first zero-centered and then filtered using a band-pass Butterworth filter (20–450 Hz) to remove movement artifacts and environmental noise. This band-pass is widely recommended in the literature, as it effectively captures the dominant frequency components of surface EMG signals while minimizing motion artifacts and high-frequency noise. The signals were smoothed with a 50 ms window width and rectified to a single phase after filtering. Muscle activation in each phase was calculated using the root mean square (RMS) method and normalized according to MVIC values to ensure inter-individual comparability. As part of the normalization procedure, isometric MVIC measurements were taken from each participant at 100° knee extension and 45° knee flexion angles; the RMS values recorded during exercise were divided by these MVIC values to obtain the percentage activation levels (De Luca, 1997; Konrad, 2005). The obtained EMG data were analyzed using MATLAB 2023b (MathWorks, USA) for signal processing and quantitative analysis.

Ground reaction force data were collected using a Kistler force platform. Raw force data were processed and organized using Microsoft Excel software for preliminary data handling; the tare value recorded before each exercise was added in the analysis to calculate the force values in Newtons for the eccentric and concentric phases. The maximum GRF values obtained were normalized by dividing them by the participants' body weights, thereby minimizing the effect of individual differences (Jensen & Ebben, 2007; Ortega et al., 2010).

Statistical Analysis

All data obtained from the study were transferred to a computer environment. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS), version 26.0 (IBM SPSS Corp., Armonk, NY, USA). After calculating the mean ($\bar{X}$) and standard deviation (SD) values descriptively, the Shapiro–Wilk test was applied for the normality analysis of the study. According to the normality analysis, repeated measures ANOVA was used to compare the results of the eccentric and concentric contraction phases obtained from the different FL step exercises, the right-left leg results, and the GRF results. The Bonferroni post-hoc analysis, one of the multiple comparison tests, was applied to determine which application had the advantage. For better interpretation of the data, significance was set at $p < .05$. Effect sizes were interpreted as small (0.20-0.49), medium (0.50–0.79), and large (>0.80) (Cohen, 1988).

Results

Upon examining Table 1, the average age of the athletes was 21.28 ± 1.84; the average height was 176.86 ± 0.04; the average body weight was 72.59 ± 9.47; the average sporting age was 9.47 ± 2.48; the average BMI was 23.18 ± 2.49.

As shown in Table 2, no statistically significant differences were observed between the groups for the left or right leg in the eccentric phase for any muscle group, including the biceps femoris (BF; ES = 0.28 [small] and 0.72 [medium]), vastus lateralis (VL; ES = 0.27 [small] and 0.78 [medium]), rectus femoris (RF; ES = 0.38 [small] and 0.42 [small]), and vastus medialis (VM; ES = 0.15 [small] and 0.40 [small]) (all $p > .05$).

As shown in Table 3, no statistically significant differences were observed between the groups for the left or right leg in the concentric phase for any muscle group, including the biceps femoris (BF; ES = 0.40 and 0.43 [small]), vastus lateralis (VL; ES = 0.12 and 0.15 [small]), rectus femoris (RF; ES = 0.04 and 0.28 [small]), and vastus medialis (VM; ES = 0.07 and 0.19 [small]) (all $p > .05$).

As shown in Table 4, statistically significant differences were observed between the groups for the concentric (CON) and eccentric (ECC) phase variables of both the right and left legs (CON right, ECC right, CON left, and ECC left; ES = 3.66, 3.23, 4.55, and 5.50, respectively [all large]) (all $p < .05$). Post hoc analysis showed the following ranking for both legs in the concentric and eccentric phases: 15 cm resistance band-assisted forward lunge (FL) > 0 cm resistance band-assisted FL > 15 cm unassisted FL > 0 cm (flat surface) FL.

Discussion

This study aimed to compare lower extremity muscle activation and GRF values during four different FL variations performed with and

Table 2.
Comparison of Muscle Activation Levels During the Eccentric Phase of Forward Lunge Variations Normalized to MVIC (N = 21)

		Left Leg				Right Leg			
Muscles	**Groups**	**X ± SD**	**F**	***p***	**Significance**	**X ± SD**	**F**	***p***	**Significance**
BF	0 cm resistance band-assisted FL	13.82 ± 9.75	0.773	.512	–	14.88 ± 7.45	2.077	.110	–
	0 cm (flat ground) FL	12.35 ± 8.13				12.56 ± 5.06			
	15 cm resistance- assisted band FL	17.06 ± 13.54				18.88 ± 10.37			
	15 cm no assisted band FL	16.22 ± 12.77				16.99 ± 10.50			
VL	0 cm resistance band-assisted FL	99.55 ± 35.70	0.748	.527	–	104.01 ± 39.53	2.095	.107	–
	0 cm (flat ground) FL	97.99 ± 47.14				99.94 ± 36.20			
	15 cm resistance- assisted band FL	115.18 ± 40.35				128.51 ± 39.83			
	15 cm no assisted band FL	107.75 ± 44.52				114.61 ± 45.47			
RF	0 cm resistance band-assisted FL	110.28 ± 38.75	1.072	.366	–	62.05 ± 38.02	1.171	.326	–
	0 cm (flat ground) FL	104.79 ± 44.77				55.91 ± 31.04			
	15 cm resistance- assisted band FL	126.58 ± 40.87				76.91 ± 40.77			
	15 cm no assisted band FL	120.14 ± 47.97				68.84 ± 42.08			
VM	0 cm resistance band-assisted FL	100.35 ± 39.25	0.430	.732	–	107.66 ± 43.42	1.122	.345	–
	0 cm (flat ground) FL	99.34 ± 47.03				97.20 ± 41.76			
	15 cm resistance- assisted band FL	111.20 ± 30.90				121.23 ± 41.55			
	15 cm no assisted band FL	107.60 ± 41.11				111.66 ± 45.32			

BF, biceps femoris; F, F statistic; FL, forward lunge; N, sample size; P, significance level; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.

without resistance band assistance. The primary finding of the study was that GRF values increased significantly under conditions involving greater mechanical demand, particularly when the exercise was performed from a height of 15 cm and when resistance band assistance was applied.

In general, GRF values increased across all experimental conditions compared to the flat ground (0 cm) condition. The greatest increases were observed in the 15 cm height conditions, particularly when combined with resistance band assistance. Overall, GRF values increased by approximately 50%–60% in the 15 cm conditions, while resistance band assistance contributed an additional increase of approximately 20%–30%.

Detailed percentage differences between conditions are presented in Table 4. This increase can be explained by the greater mechanical demand associated with higher descent velocity and impact conditions. Increased movement velocity and impact intensity require greater deceleration during the braking phase, which leads to higher GRFs (McMahon et al., 2022; Verniba et al., 2017). In this context, the increased drop height likely elevated both momentum and impact forces, resulting in higher GRF values.

These findings are consistent with previous literature reporting that increases in drop height lead to higher impact forces and loading rates. Greater fall height results in increased momentum at ground contact, thereby elevating peak GRFs and eccentric loading demands (Smeets et al., 2021; Barker and Harry , 2022; La Greca et al., 2024). Similarly, previous studies have reported that FL variations performed under increased mechanical constraints result in higher GRF values (Park et al., 2021; Günay & Gülmez, 2023; Günay, 2024).

While mechanical outputs showed clear increases across conditions, the neuromuscular responses did not follow the same pattern, indicating a potential dissociation between external loading and muscle activation.

In contrast to GRF findings, muscle activation values did not show statistically significant differences across the different FL variations. Although some increases in muscle activation (approximately 10%–25%) were observed in certain conditions, these differences were not statistically significant.

The lack of statistical significance despite observable increases may be attributed to the inherent variability of EMG signals and the complex relationship between muscle activation and external force production. EMG amplitude does not always scale proportionally with external force due to motor unit recruitment strategies, neuromuscular redundancy, and coordination between synergistic muscles (Vigotsky et al., 2022; Hug et al., 2015).

A possible explanation for the relatively stable EMG activity across conditions is that lower extremity muscles in closed kinetic chain exercise primarily function to ensure joint stability and control rather than directly scaling force output. In such tasks, the central nervous system may adopt a consistent motor control strategy, distributing the mechanical load across multiple joints and muscle groups to maintain movement efficiency (Latash, 2012; Hug et al., 2015). This strategy reduces the need for substantial increases in activation amplitude, even when external mechanical demand increases. Furthermore, co-contraction between agonist and antagonist muscle groups may contribute to joint stability without significantly altering overall EMG amplitude, which may partially explain the absence of statistically significant differences (Vigotsky et al., 2022; Thomas et al., 2022; Paredes et al., 2024).

These findings are consistent with previous studies reporting limited changes in muscle activation across different lunge variations. For example, Muyor et al. (2020) reported no significant differences in RF activation between different FL conditions. Similarly, Escamilla et al. (2012) indicated that variations in step length and knee angle had limited influence on muscle activation patterns, suggesting

Table 3.
Comparison of Muscle Activation Levels During the Concentric Phase of Forward Lunge Variations Normalized to MVIC (N = 21)

		Left Leg				Right Leg			
Muscles	**Groups**	**X ± SD**	**F**	***p***	**Significance**	**X ± SD**	**F**	***p***	**Significance**
BF	0 cm resistance band-assisted FL	13.72 ± 7.23	1.121	.345	–	14.17 ± 9.14	1.216	.309	–
	0 cm (flat ground) FL	12.52 ± 6.45				12.78 ± 7.87			
	15 cm resistance- assisted band FL	16.68 ± 8.96				17.97 ± 10.37			
	15 cm no assisted band FL	14.19 ± 7.35				15.60 ± 9.24			
VL	0 cm resistance band-assisted FL	73.91 ± 30.57	0.328	.805	–	82.92 ± 32.40	0.430	.732	–
	0 cm (flat ground) FL	73.33 ± 35.86				85.51 ± 37.14			
	15 cm resistance- assisted band FL	81.61 ± 32.62				89.99 ± 33.61			
	15 cm no assisted band FL	80.52 ± 38.98				94.65 ± 40.51			
RF	0 cm resistance band-assisted FL	81.63 ± 26.71	0.127	.944	–	42.76 ± 19.80	0.773	.512	–
	0 cm (flat ground) FL	82.92 ± 33.27				45.79 ± 24.24			
	15 cm resistance- assisted band FL	85.69 ± 31.96				53.07 ± 29.02			
	15 cm no assisted band FL	87.45 ± 41.77				51.80 ± 28.02			
VM	0 cm resistance band-assisted FL	77.86 ± 33.64	0.198	.897	–	71.79 ± 28.20	0.541	.656	–
	0 cm (flat ground) FL	78.07 ± 34.50				73.53 ± 26.96			
	15 cm resistance- assisted band FL	83.84 ± 30.49				77.49 ± 29.61			
	15 cm no assisted band FL	83.76 ± 39.53				82.50 ± 33.31			

BF, biceps femoris; F, F statistic; FL, forward lunge; N, sample size; P, significance level; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.

that lower extremity muscles primarily function to maintain stability and control during such tasks. Similarly, López-de-Celis et al. (2024) reported differences in quadriceps and gluteus medius activity depending on loading stability, highlighting that changes in exercise conditions do not necessarily produce uniform changes in muscle activation across muscles.

Furthermore, the highest muscle activation values were observed in the VM muscle for the right leg and the RF muscle for the left leg under the 15 cm resistance band-assisted condition. However, these differences were not statistically significant, indicating that increased mechanical loading does not necessarily translate into proportional increases in muscle activation. Bilateral differences in muscle morphology may also contribute to variability in muscle activation between the right and left limbs. Kulas et al. (2018) reported that healthy individuals may exhibit subject- and muscle-specific asymmetries in quadriceps and hamstring muscle volume, highlighting the importance of considering individual bilateral differences when interpreting lower-extremity muscle responses. Similarly, Sanders et al. (2018) demonstrated bilateral asymmetries in rectus femoris characteristics among healthy athletes, highlighting the importance of considering individual bilateral differences when interpreting lower-extremity muscle responses.

Another important consideration is the difference between eccentric and concentric contraction phases. Although no significant differences were observed in EMG amplitudes between these phases, eccentric contractions are known to produce higher force outputs with lower metabolic cost due to both neural and mechanical factors, including the contribution of passive elastic components within the muscle–tendon unit (Douglas et al., 2017; Suchomel et al., 2018; Hody et al., 2019). In the present study, the higher GRF values observed, particularly under increased height conditions, support the dominant role of eccentric loading during the braking phase of the movement.

The findings of this study suggest a partial dissociation between neuromuscular activation and mechanical output. While GRF values increased significantly with increasing mechanical demand, EMG activity remained relatively stable across conditions. This dissociation can be explained by the fact that GRF reflects the external mechanical load imposed on the body, whereas EMG represents the neural activation required to perform the movement. In multi-joint functional exercises such as the FL, the central nervous system may maintain a relatively stable activation strategy while distributing load across multiple muscles and joints.

Additionally, the relatively low and non-significant changes in EMG activity may be related to the contribution of other lower extremity muscles that were not measured in this study. Muscles such as the gastrocnemius and soleus play an important role in force absorption and propulsion during dynamic tasks such as landing and stepping movements. Previous research has shown that these muscles can significantly contribute to joint stabilization and load distribution during such movements (Walsh et al., 2012; McGowan et al., 2008; Neptune et al., 2001). Therefore, the inclusion of additional muscles in future studies may provide a more comprehensive understanding of neuromuscular responses.

Overall, these findings indicate that mechanical loading conditions play a more decisive role in determining GRF outcomes, whereas muscle activation patterns remain relatively consistent across functional movement variations. This supports the notion that neuromuscular control strategies are task-specific and may prioritize movement stability over modulation of force output. From a practical perspective, FL variations involving increased mechanical demand, such as stepping from a height, may be more effective for developing strength and power due to their greater mechanical loading characteristics. In contrast, resistance band-assisted variations may be more appropriate for improving movement control, coordination, and joint stability.

Table 4.
Comparison of Ground Reaction Forces Between Right and Left Legs Across Phases During the Forward Lunge Exercise According to Groups

		Right Leg				Left Leg			
Phases	Groups	X ± SD	F	*p*	Significance	X ± SD	F	*p*	Significance
Concentric	0 cm resistance band-assisted FL (N)	1023.97 ± 289.34	15.443	.000	c > a > d > b	1057.95 ± 224.06	22.264	.000	c > a > d > b
	0 cm (flat ground) FL (N)	788.43 ± 108.88				761.66 ± 106.88			
	15 cm resistance- assisted band FL (N)	1246.15 ± 275.81				1247.96 ± 286.87			
	15 cm no assisted band FL (N)	901.46 ± 193.10				977.42 ± 95.24			
Eccentric	0 cm resistance band-assisted FL (N)	994.85 ± 248.12	12.738	.000	c > a > d > b	1034.65 ± 187.38	32.716	.000	c > a > d > b
	0 cm (flat ground) FL (N)	734.71 ± 117.27				747.38 ± 64.58			
	15 cm resistance- assisted band FL (N)	1127.83 ± 211.87				1152.75 ± 189.28			
	15 cm no assisted band FL (N)	955.39 ± 235.76				891.04 ± 64.57			

F, F statistic; FL, forward lunge; N, newton; P, significance level.
[a]0 cm resistance band-assisted forward lunge.
[b]0 cm (flat ground) forward lunge.
[c]15 cm resistance band-assisted forward lunge.
[d]15 cm forward lunge without a resistance band.

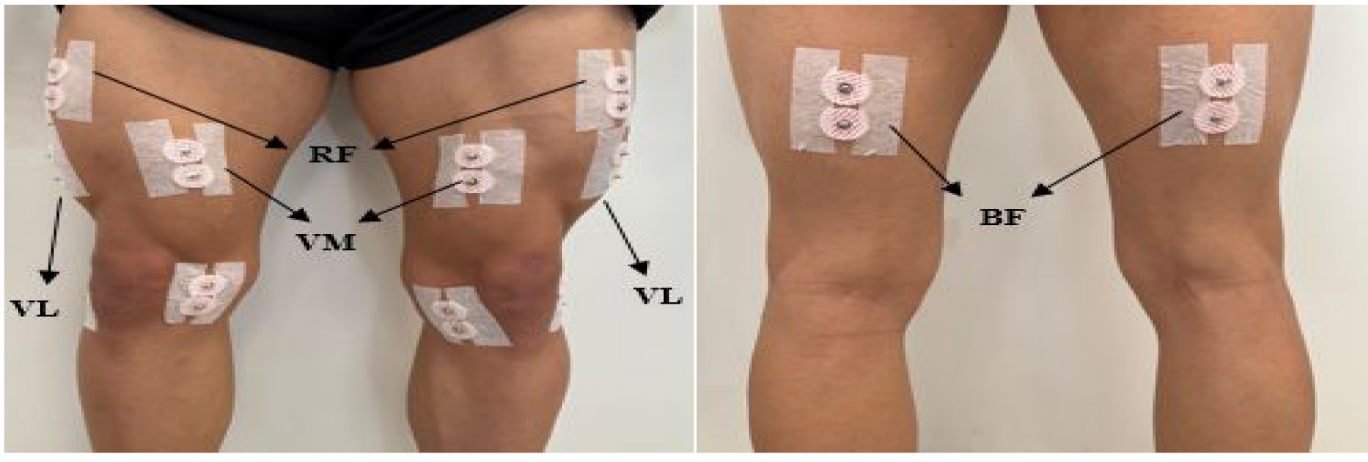

Figure 2.
Placement of Surface Electromyography (sEMG) Electrodes on the Rectus Femoris (RF), Vastus Medialis (VM), Vastus Lateralis (VL), and Biceps Femoris (BF) Muscles in Accordance with SENIAM Recommendations.

Therefore, exercise selection should be aligned with specific training objectives (Suchomel et al., 2018).

This study was conducted to compare lower extremity muscle activations and GRF values during four different forward step exercises performed with and without resistance band assistance. The findings revealed no significant difference in muscle activation values between the FL variations; however, GRF values increased significantly, particularly in variations involving a 15 cm height. These results indicate that neuromuscular activation remains largely constant in a functional exercise such as the FL, but that external mechanical loading patterns have a strong effect on the mechanical outputs of the movement.

It shows that FL step exercises create similar neuromuscular demands in terms of muscle activation, but that the form of mechanical loading is decisive in GRFs. Therefore, it may be advisable to prefer FL step variations performed from a height of 15 cm in single-leg eccentric and concentric strength development-focused training programs, and resistance band-assisted variations in balance and stability-focused training.

Considering the GRF increases in FL step types applied according to height, exercise preferences can be recommended as follows: for beginners, first on flat ground (0 cm), and for those with intermediate exercise experience, FL steps from a 15 cm height. For advanced and elite athletes, FL step exercises on flat ground (0 cm) and with band assistance may be recommended in that order. The forward step exercise performed from a height of 15 cm with band assistance generates the highest GRF, making it a high-difficulty application for individuals who are new to the sport, returning to training to get back on the field, or returning to the sport after a lower extremity injury. Therefore, exercise progression from low GRF values to high GRF values should be preferred.

Future studies could expand these findings by examining the effects of different resistance levels (e.g., assisted bands with different tensions, such as 25 cm and 75 cm) and different fall heights (e.g., 20–40 cm height) on muscle activation and GRF.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

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Informed Consent: Written informed consent was obtained from all participants before participation in the study.

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