

Evaluation of lower-limb muscle performance using amplitude, variability, and spectral characteristics during vertical jumping in basketball players

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Abstract:

Vertical jump is a key indicator for evaluating athletes' explosive power, neuromuscular efficiency, and fatigue resistance. Surface electromyography (sEMG) provides a non-invasive method to assess muscle electrical activity and is widely used in sports biomechanics and rehabilitation research. In this study, the electromyographic activity of the thigh and calf muscles—specifically the Rectus Femoris (RF), Gluteus Maximus (GM), Gastrocnemius Medialis (GMM), and Biceps Femoris Caput Longus (BFCL)—was analyzed during vertical jumps, focusing on amplitude, variability, and spectral characteristics. The study sample included 17 male athletes (mean $\pm$ SD: age 16.24 ± 1.2 years; height 179.6 ± 7.7 cm; weight 66.8 ± 14.4 kg). EMG signals were recorded using the FREEEMG system (BTS Bioengineering, Italy) at a sampling frequency of 1000 Hz and filtered within a 20–450 Hz bandwidth for analysis. Feature extraction, including RMS, MAV, VAR, WL, SSCr, MDF, and MNF, was performed using MATLAB R2024a (MathWorks, USA). The results indicated that the RF and GM were the primary contributors to explosive force during the jump's take-off phase, exhibiting stable RMS (0.10–0.11 mV) and MAV (120–130 μ V) values consistently across all three trials. In contrast, the GMM and BFCL showed a gradual decline in both amplitude and frequency features (BFCL MDF $\approx 42.8 \rightarrow 40.3$ Hz; GM MDF $\approx 104.8 \rightarrow 102.3$ Hz), suggesting the onset of muscular fatigue. In terms of variability features (VAR, WL, SSCr, and ZCR), the GM and RF maintained stability even under fatigue, whereas the GMM and BFCL exhibited reduced signal complexity, likely owing to deactivation of fast-twitch (FT) fibers. The thigh muscles served as the primary generators of explosive force, while the calf muscles primarily contributed to stabilization and movement completion. The functional specialization of the muscles followed the order: GM $\approx$ RF > GMM > Biceps Femoris. These findings offer a scientific foundation for optimizing load distribution and monitoring fatigue in sports training.

Keywords: electromyography, vertical jump, muscle activity, neuromuscular fatigue, explosive power, biomechanical analysis

Introduction

The vertical jump is widely used in sports as a standard measure for assessing strength, speed, and explosive power. Studies have shown that jump height reflects the capacity of lower limb muscles to generate maximal force and serves as an indicator of neuromuscular efficiency (Markovic & Mikulic, 2010). Furthermore, the vertical jump is a common test for evaluating lower limb explosive strength and is recognized as an important marker of overall athletic preparedness and muscular function (Santos et al., 2022). It is also closely related to speed, explosive strength, and jumping performance in many sports—particularly basketball, volleyball, and handball—and is considered a reliable predictor of athletic performance (Sheppard & Doyle, 2008). Research has demonstrated that vertical jump height directly reflects an athlete's explosive power, speed–strength capacity, and responsiveness to plyometric training (McMahon et al., 2018; Joldasbaeva, 2025). Therefore, this test is widely used not only to assess general physical preparedness but also to evaluate competition readiness and an athlete's potential for high performance during gameplay (Gathercole, Sporer & Stellingwerff, 2015).

In basketball players, vertical jump performance is closely associated with game activity. Specifically, force–time parameters obtained from the countermovement jump (CMJ) test show a significant positive correlation ($r \approx 0.40\text{--}0.55$) with players' on-court playing time and overall performance efficiency (Cabarkapa et al., 2024). Additionally, research has revealed a strong association between vertical jump ability and playing position, with significant differences in maximal jump height and anthropometric characteristics observed among players in different court roles (Pehar et al., 2017).

Surface electromyography (sEMG) allows non-invasive recording of muscle electrical activity through electrodes placed on the skin. This technique captures the bioelectrical signals generated during muscle fiber contraction and is widely used in sports training, rehabilitation, and biomechanical research (De Luca, 1997; Merletti & Farina, 2016). By analyzing amplitude, variability, and spectral characteristics during muscle contraction, sEMG provides insights into muscle activation levels and functional status (Mamajonov et al., 2024). These measurements provide essential information on the intensity of muscle activity, neuromuscular control, and the onset of fatigue (Dimitrov et al., 2006). Methodological standardization is essential in sEMG research to ensure accurate data interpretation and facilitate meaningful comparisons across studies. Accordingly, the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines are adopted as the methodological reference for electrode selection, placement, and signal processing (Hermens et al., 1999). Adhering to these standards ensures the reliability, reproducibility, and international comparability of research findings.

Several key features are commonly used to evaluate muscle activity in research. Amplitude-based features provide insights into the intensity of muscle activation and force generation. Specifically, the Root Mean Square (RMS) quantifies the overall electrical activity and energy expenditure of the muscle, while the Mean Absolute Value (MAV) reflects the general level of muscle activation (Chen et al., 2020). The Mean Absolute Deviation (MAD) indicates the variability in muscle signals (Castruita-López et al., 2025), and the Wilson Amplitude (WAMP) detects active contraction episodes by counting instances where the signal amplitude exceeds a predefined threshold (Phinyomark et al., 2012). Variability and complexity features are essential for assessing the stability of muscle activity and monitoring fatigue development. Variance (VAR) reflects the degree of instability in muscle activation, while Waveform Length (WL) captures the complexity of the EMG signal waveform. Slope Sign Change (SSCR) quantifies the number of rapid fluctuations in muscle activity, and Zero Crossing Rate (ZCR) indicates how frequently the signal crosses the zero line, providing information on the rapidity of muscle activation (He et al., 2024; Toledo-Pérez et al., 2019). Additionally, spectral and frequency-based features are used to identify muscle fiber types and evaluate the dynamics of fatigue progression. Median Frequency (MDF) and Mean Frequency (MNF) reflect the activity of fast- and slow-twitch muscle fibers (Chen et al., 2020). Spectral Centroid (SC) and Spectral Dispersion (SD) describe the distribution and spread of dominant frequencies in the muscle signal, while Bandwidth (BW) measures the overall frequency range of muscle activity (Hellara et al., 2024). Spectral Slope (SS) represents the balance between low- and high-frequency components, and Band Power Ratio (BPR) indicates how the signal energy is distributed across different frequency bands (Wei & Chowdhury, 2025).

By integrating amplitude-, variability-, and spectral-based features, it is possible to accurately evaluate muscle functional status, fatigue resistance, and neuromuscular efficiency (Chang et al., 2016). This approach provides a scientific basis for analyzing explosive power, stability, and fatigue mechanisms in the thigh and calf muscles during vertical jumps.

Timely detection of muscle fatigue is particularly important in sports training and rehabilitation (Al-Ayyad et al., 2023). Monitoring fatigue processes helps optimize training load, prevent overexertion, and reduce injury risk in athletes. In rehabilitation settings, it is used to track muscle recovery and to develop effective, individualized treatment programs (Rampichini et al., 2020).

In vertical jumping, the thigh muscles are the primary source of power. The quadriceps group—including the Rectus Femoris (RF), Vastus Lateralis, and Vastus Medialis—plays a central role during the take-off phase by generating strong knee extension, which directly affects jump height (Bobbert & van Soest, 2001). The Gastrocnemius Medialis (GMM) contributes to plantar flexion, adding speed and power at the end of the take-off phase. In contrast, the Tibialis Anterior acts as an antagonistic muscle, maintaining balance and foot stability during the movement (Lees, Vanrenterghem & De Clercq, 2004). Thus, while the quadriceps provide the main propulsive force, the calf muscles primarily serve stabilizing and movement-finalizing functions during the jump. The coordination between the thigh and calf muscles is a critical biomechanical factor influencing vertical jump performance (Markovic & Mikulic, 2010). These muscles are essential for generating explosive power, maintaining balance during the movement, and enhancing fatigue resistance under prolonged loading. The functional contributions of the quadriceps and calf muscles largely determine an athlete's effective jumping ability and overall physical preparedness (Markovic & Mikulic, 2010; Bobbert & van Soest, 2001).

While previous studies have typically examined either the amplitude or frequency characteristics of EMG signals in isolation, this research takes a comprehensive approach by analyzing amplitude, variability, and spectral features together. This multifaceted analysis enables a deeper evaluation of muscle functional status,

more accurate identification of fatigue mechanisms, and a broader assessment of changes in neuromuscular control. Examining the electromyographic activity of the thigh and calf muscles during vertical jumps allows for a detailed assessment of athletes' preparedness. EMG analysis provides insights into muscle activation sequences, activity levels, and intermuscular coordination, facilitating individualized evaluation of each muscle's contribution to jump performance, force production efficiency, fatigue resistance, and movement quality. The primary objective of this study was to analyze the electromyographic activity of the thigh and calf muscles during vertical jumps based on amplitude, variability, and spectral features, and to determine their functional roles and intermuscular coordination mechanisms.

Materials and methods

Participants

Seventeen male basketball players who trained regularly participated in the study. Their mean ($\pm$ standard deviation) age was 16.82 ± 2.48 years, height 179.65 ± 7.71 cm, body mass 66.8 ± 14.4 kg, and body mass index (BMI) 20.54 ± 3.2 .

Table 1. Characteristics of the study group

	Min	Max	Mean	Standard deviation
Age	15	18	16.24	1.2
Height	160	188	179.65	7.7
Weight	46.4	105	66.8	14.4
BMI	15.93	29.7	20.5	3.2

All participants were healthy and reported no history of lower-limb muscle or joint injuries, nor any clinical complaints within the past six months. Prior to the experiment, participants and their parents or legal guardians were fully informed about the research procedures and potential risks, and written informed consent was obtained. A preliminary medical examination confirmed the absence of cardiovascular, neurological, or musculoskeletal limitations. All athletes trained regularly and were physically prepared to participate in the experimental procedures.

Experimental Design

During the experimental session, participants performed three countermovement jumps (CMJs) following a standardized testing protocol. For each jump, muscle bioelectrical activity was recorded during the concentric (propulsion), eccentric (landing), and stabilization phases. A brief recovery period of 30 s was provided between jumps to ensure adequate physiological recovery. This approach allowed for the assessment of muscle responses under conditions closely resembling actual sports performance.

Equipment and Measurements

Muscle bioelectrical activity was recorded using a high-precision wireless sEMG system (FREEEMG; BTS Bioengineering, Italy) equipped with load-resistant and motion-tolerant surface electrodes. This system enables real-time monitoring of muscle activation during dynamic athletic tasks, ensuring the reliable acquisition of high-quality EMG signals.



Figure 1. Equipment used for surface electromyography (sEMG) measurements: (a) reusable EMG sensors; (b) disposable Ag/AgCl-based 3M Red Dot™ electrodes

Surface electrodes were positioned following the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) international guidelines. EMG signals were recorded from the following key muscles:

- Biceps Femoris Caput Longus (BFCL): located on the posterior thigh, responsible for eccentric control and postural stabilization;
- Gastrocnemius Medialis (GMM): a major calf muscle involved in plantar flexion and explosive propulsion during take-off;
- Gluteus Maximus (GM): the main hip extensor, contributing to force generation during the propulsive phase;
- Rectus Femoris (RF): part of the quadriceps group, actively engaged in knee extension and hip flexion during the upward phase of the jump.

The EMG signals were sampled at 1000 Hz. To reduce noise, a 20 Hz high-pass filter was applied to remove low-frequency components, while a 450 Hz low-pass filter eliminated high-frequency artefacts. Additionally, a 50 Hz notch filter was used to minimize electrical interference from the power line.

These settings ensured high-precision recording of muscle functional activity during sport-specific loading and provided optimal conditions for subsequent mathematical and statistical analysis of the data.

EMG Features

During signal processing, a range of features was extracted to assess the amplitude, variability, complexity, and spectral–frequency characteristics of muscle activity. These measures offered a comprehensive characterization of both the temporal and frequency-domain properties of the recorded EMG signals.

Amplitude Features

Root Mean Square (RMS): represents the mean quadratic value of the EMG signal, reflecting the intensity of muscle activation. It indicates overall electrical activity and the muscle's potential for force generation (Chang et al., 2016).

Mean Absolute Value (MAV): denotes the mean absolute amplitude, representing the general level of muscle activity during the contraction (Chen et al., 2020).

Mean Absolute Deviation (MAD): describes the mean absolute deviation of the EMG signal, characterizing variability in muscle activation (Castruita-López et al., 2025).

Wilson Amplitude (WAMP): indicates the number of times the EMG signal amplitude exceeds a predefined threshold, reflecting episodes of active muscle contraction (Phinyomark et al., 2012; Castruita-López et al., 2025).

Variability and Complexity Features

Variance (VAR): represents the degree of signal dispersion, reflecting the instability or variability of muscle activity (Chen et al., 2020).

Waveform Length (WL): refers to the total length of the EMG waveform, serving as an indicator of signal complexity and capturing changes in both frequency and amplitude domains (He et al., 2024).

Slope Sign Change Ratio (SSCR): denotes the number of slope sign changes in the EMG signal, reflecting high-frequency components and the dynamic characteristics of muscle activation (He et al., 2024).

Zero Crossing Rate (ZCR): measures how frequently the EMG signal crosses the zero line, indicating the rapidity and oscillatory nature of muscle activity (Toledo-Pérez et al., 2019).

Spectral and Frequency-Domain Features

Median Frequency (MDF) and Mean Frequency (MNF): frequency-based features indicating the degree of recruitment of high- or low-frequency muscle fibers, reflecting the muscle's activation patterns and fatigue tendencies (Chen et al., 2020).

Spectral Centroid (SC): represents the spectral center of gravity, describing the distribution of dominant frequencies in the EMG signal (Hellara et al., 2024).

Spectral Dispersion (SD): measures the spread or variability of frequency components, characterizing the width of the spectral distribution (Hellara et al., 2024).

Bandwidth (BW): defines the range of frequency content, reflecting the overall spectral coverage of muscle activity (Hellara et al., 2024).

Spectral Slope (SS): describes the balance between low- and high-frequency components, serving as an indicator of spectral changes associated with fatigue (Wei & Chowdhury, 2025).

Band Power Ratio (BPR): represents the proportion of signal power distributed across specific frequency bands, providing information on the energy contribution of different spectral regions to muscle activity (Wei & Chowdhury, 2025).

Data Processing

The acquired EMG signals were processed and analyzed using MATLAB R2024a (MathWorks, USA). Raw signals were filtered, denoised, and standardized to enable quantitative analysis. Descriptive statistics, including the mean ($\bar{x}$) and standard deviation (σ), were computed. Comparative analyses between the right and left limbs were performed to assess variations in amplitude, variability, and frequency-domain features. Intermuscular differences were evaluated with particular focus on fatigue resistance, force contribution, and the functional role in postural stability. During result interpretation, muscle activation patterns were examined across three key phases—propulsion (concentric), landing (eccentric), and stabilization—emphasizing the adaptability of fatigue dynamics and neuromuscular coordination throughout the vertical jump.

Results

Analysis of Amplitude Features of Thigh and Calf Muscles

Jumping is a fundamental biomechanical movement in basketball, and evaluating the EMG activity of lower limb muscles during this action is essential for understanding their contributions to explosive power, balance, and landing mechanics. Amplitude-related features—RMS, MAV, MAD, and WAMP—offer valuable

insights into the level of muscle fiber activation, force-generating potential, and consistency of neuromuscular control.

In this study, a comparative analysis of the EMG activity of the BFCL, GMM, GM, and RF muscles in the right and left legs was performed to identify their differential functional roles during jumping. This approach provides a scientific foundation for training strategies aimed at enhancing explosive strength, improving jump performance, and reducing the risk of lower-limb injuries in athletes. The BFCL, located in the posterior thigh, plays a key role during both the propulsion and landing phases of the jump. The results showed higher RMS and MAV values for the right leg ($= 0.068\text{--}0.077\text{ mV}$; $89.5\text{--}97.3\text{ }\mu\text{V}$), indicating active involvement in explosive force generation. Elevated MAD and WAMP values, reflecting greater dispersion, highlighted the dynamic and variable nature of muscle activation. In contrast, the left leg exhibited lower RMS and MAV values ($= 0.056\text{--}0.064\text{ mV}$; $73.2\text{--}80.3\text{ }\mu\text{V}$) with smaller standard deviations, suggesting a stabilizing function during the landing phase. These findings indicate that the BFCL primarily contributes to explosive power generation in the right leg, while in the left leg, it predominantly supports postural balance and impact control.

Table 1. Comparative analysis of electromyographic amplitude features of thigh and calf muscles between the right and left legs (n = 17)

Muscle	Right/ Left	Jumps	RMS ($\bar{x} \pm \sigma$)	MAV ($\bar{x} \pm \sigma$)	MAD ($\bar{x} \pm \sigma$)	WAMP ($\bar{x} \pm \sigma$)
BFCL	Right	1	0.077 ± 0.051	97.356 ± 51.402	47.206 ± 35.36	0.497 ± 0.107
		2	0.068 ± 0.026	89.512 ± 32.775	40.318 ± 17.718	0.473 ± 0.090
		3	0.072 ± 0.044	90.878 ± 46.024	41.721 ± 27.703	0.459 ± 0.116
	Left	1	0.064 ± 0.029	80.292 ± 23.099	37.618 ± 16.765	0.485 ± 0.130
		2	0.056 ± 0.021	73.252 ± 17.499	33.944 ± 12.479	0.492 ± 0.141
		3	0.061 ± 0.036	76.025 ± 30.392	34.491 ± 16.164	0.474 ± 0.111
GMM	Right	1	0.093 ± 0.041	113.648 ± 42.782	46.297 ± 21.809	0.556 ± 0.116
		2	0.089 ± 0.043	109.952 ± 41.751	43.862 ± 20.501	0.544 ± 0.107
		3	0.085 ± 0.039	103.746 ± 39.521	40.997 ± 22.349	0.519 ± 0.136
	Left	1	0.086 ± 0.033	107.119 ± 29.227	45.962 ± 20.331	0.559 ± 0.138
		2	0.079 ± 0.034	99.917 ± 28.881	41.341 ± 15.98	0.536 ± 0.103
		3	0.082 ± 0.037	101.155 ± 36.197	41.068 ± 23.42	0.516 ± 0.139
GM	Right	1	0.102 ± 0.049	129.409 ± 49.528	54.341 ± 26.275	0.503 ± 0.131
		2	0.097 ± 0.043	124.24 ± 42.127	49.782 ± 18.643	0.492 ± 0.077
		3	0.101 ± 0.042	130.322 ± 45.91	53.974 ± 29.05	0.486 ± 0.116
	Left	1	0.101 ± 0.059	129.648 ± 64.678	57.682 ± 39.321	0.518 ± 0.143
		2	0.086 ± 0.039	114.2 ± 51.229	49.1 ± 27.055	0.492 ± 0.131
		3	0.096 ± 0.045	128.88 ± 59.417	59.688 ± 35.899	0.507 ± 0.138
RF	Right	1	0.105 ± 0.063	129.871 ± 64.84	51.891 ± 28.89	0.483 ± 0.096
		2	0.103 ± 0.065	130.921 ± 70.205	54.965 ± 30.961	0.496 ± 0.108
		3	0.103 ± 0.065	129.141 ± 67.032	54.262 ± 34.392	0.486 ± 0.126
	Left	1	0.108 ± 0.063	136.007 ± 64.679	55.685 ± 29.763	0.508 ± 0.114
		2	0.097 ± 0.055	122.193 ± 55.265	50.479 ± 23.625	0.484 ± 0.102
		3	0.099 ± 0.051	128.363 ± 57.782	54.515 ± 25.893	0.509 ± 0.098

As the primary plantar flexor, the GMM plays a key role in generating jump height and explosive power. In the right leg, higher RMS and MAV values ($= 0.085\text{--}0.093\text{ mV}$; $103.7\text{--}113.6\text{ }\mu\text{V}$) indicated greater muscle involvement during the propulsion phase. The left leg exhibited slightly lower RMS and MAV values ($= 0.079\text{--}0.086\text{ mV}$; $99.9\text{--}107.1\text{ }\mu\text{V}$), while smaller standard deviations suggested more consistent and stable muscle activation. WAMP values ($0.516\text{--}0.559$) were relatively more stable in the left leg, supporting the muscle's role in landing control and balance maintenance. Overall, the GMM was highly active in force production for both limbs, contributing more to explosive propulsion in the right leg and to stabilization and balance in the left leg. As the primary hip extensor, the GM plays a key role during the propulsion phase of the jump. In the right leg, higher RMS and MAV values ($= 0.097\text{--}0.102\text{ mV}$; $124.2\text{--}130.3\text{ }\mu\text{V}$) indicated consistent recruitment for maximal force generation. The left leg showed comparable RMS and MAV values ($= 0.086\text{--}0.101\text{ mV}$; $114.2\text{--}129.6\text{ }\mu\text{V}$), but a wider range of standard deviations suggested greater variability in muscle activation.

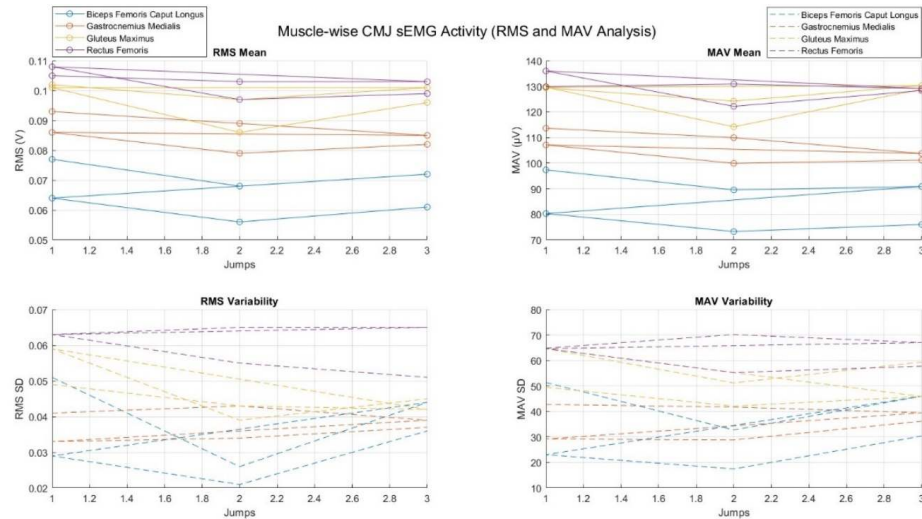


Figure 2. Dynamics of electromyographic activity (RMS and MAV) of lower-limb muscles across three consecutive vertical jumps

The RF, as part of the quadriceps group, plays a crucial role in hip flexion and knee extension during the jump. In the right leg, RMS and MAV values ($= 0.103\text{--}0.105$ mV; $129.1\text{--}130.9$ μV) were notably high, indicating the muscle's key contribution to the force required for propulsion. In the left leg, values were similarly high ($= 0.097\text{--}0.108$ mV; $122.1\text{--}136.0$ μV), though a wider range of standard deviations suggested less stable activation. Elevated MAD and WAMP values further reflected bilateral engagement of the muscle during both propulsion and landing phases. Overall, the RF demonstrated strong bilateral activity, functioning as one of the primary sources of power in vertical jump performance.

The EMG analysis revealed side-dependent differences in muscle activation amplitudes. For the BFCL, higher RMS and MAV values were observed in the right leg ($= 0.068\text{--}0.077$ mV; $89.5\text{--}97.3$ μV), indicating active involvement in generating propulsive force. The left leg showed lower amplitudes ($= 0.056\text{--}0.064$ mV; $73.2\text{--}80.3$ μV) with smaller standard deviations, reflecting more stable activation. In the GMM, RMS and MAV values were higher in the right leg ($= 0.085\text{--}0.093$ mV; $103.7\text{--}113.6$ μV), confirming its dominant role in propulsion, while the left leg exhibited slightly lower values ($= 0.079\text{--}0.086$ mV; $99.9\text{--}107.1$ μV) and more consistent WAMP indices ($0.516\text{--}0.559$), indicating a greater contribution to landing control and balance maintenance. For the GM, higher RMS and MAV values were recorded in the right leg ($= 0.097\text{--}0.102$ mV; $124.2\text{--}130.3$ μV), indicating maximal recruitment for explosive power generation. The left leg exhibited comparable mean values ($= 0.086\text{--}0.101$ mV; $114.2\text{--}129.6$ μV) but a wider range of σ , indicating more variable activation patterns. In the RF, both legs showed very high activity, with slightly higher RMS and MAV values in the right leg ($= 0.103\text{--}0.105$ mV; $129.1\text{--}130.9$ μV) and comparable amplitudes in the left leg ($= 0.097\text{--}0.108$ mV; $122.1\text{--}136.0$ μV); however, greater variability suggested less stable recruitment. Overall, the biceps femoris contributed primarily to explosive propulsion on the right side and to stabilization on the left.

In the BFCL, the right leg exhibited the highest RMS and MAV values during the first jump ($= 0.077$ mV; 97.3 μV), followed by a decline in subsequent trials ($= 0.068\text{--}0.072$ mV; $89.5\text{--}90.8$ μV), indicating early fatigue and reduced capacity for explosive force generation. In the left leg, RMS ($= 0.064 \rightarrow 0.061$ mV) and MAV ($= 80.3 \rightarrow 76.0$ μV) showed slight decreases, but smaller σ values suggested a more stable activation pattern. For the GMM, the right leg displayed a noticeable decrease in MAV from $= 113.6$ μV in the first jump to $= 103.7$ μV in the third jump, with RMS values also decreasing ($= 0.093 \rightarrow 0.085$ mV). The left leg exhibited a similar but less pronounced trend (MAV $= 107.1 \rightarrow 101.1$ μV), suggesting better endurance and less evident fatigue development compared with the right side. In contrast, the GM maintained nearly constant MAV values in the right leg ($= 129.4 \rightarrow 130.3$ μV) and stable RMS amplitudes ($= 0.102 \rightarrow 0.101$ mV), confirming its sustained capacity for propulsive force generation during repeated jumps. In the left leg, MAV slightly decreased ($= 129.6 \rightarrow 128.9$ μV) with a broader range of σ , indicating mildly variable but functionally effective activation. The RF demonstrated high and stable activation across all jumps, with right-leg MAV ($= 129.8\text{--}130.9$ μV) and RMS ($= 0.103\text{--}0.105$ mV) remaining consistent. In the left leg, MAV decreased modestly from $= 136.0$ to 128.3 μV , though overall activity remained high, with a wider range of σ indicating minor instability. Overall, the BFCL and GMM—particularly on the right side—showed greater involvement in generating explosive force but were more susceptible to fatigue. In contrast, the GM and RF maintained stable activation patterns across all three jumps, exhibiting minimal signs of fatigue. These findings suggest that the left-leg muscles contributed more to stability maintenance, whereas the right-leg muscles played a dominant role in explosive force production during repeated jump execution.

Electromyographic Variability and Complexity Features of Lower-Limb Muscles During the Jump

Evaluating muscle electromyographic activity during jumping is important not only through amplitude analysis but also by examining variability and complexity features. These measures provide insight into muscle fatigue dynamics, the level of neuromuscular control, and the functional roles of muscles in balance maintenance and propulsion. Table 2 presents a comparative analysis of VAR, WL, SSCR, and ZCR values for the thigh and calf muscles in the right and left legs. These results offer a deeper understanding of muscle fatigue resistance and functional activity across the different phases of the jump.

Table 2. Electromyographic variability and complexity indicators of thigh and calf muscles during the jump

(n=17)

Muscle	Right/ Left	Jump	VAR ($\bar{x} \pm \sigma$)	WL ($\bar{x} \pm \sigma$)	SSCR ($\bar{x} \pm \sigma$)	ZCR ($\bar{x} \pm \sigma$)
BFCL	Right	1	16.288 ± 20.872	45.008 ± 18.682	0.205 ± 0.053	0.166 ± 0.029
		2	11.923 ± 7.743	42.437 ± 15.472	0.198 ± 0.053	0.167 ± 0.027
		3	14.184 ± 15.937	40.513 ± 15.800	0.184 ± 0.047	0.160 ± 0.026
	Left	1	10.027 ± 6.590	39.506 ± 13.304	0.200 ± 0.069	0.172 ± 0.027
		2	7.797 ± 4.755	35.789 ± 10.839	0.198 ± 0.063	0.168 ± 0.024
		3	9.712 ± 10.589	76.025 ± 30.392	34.491 ± 16.164	0.474 ± 0.111
GMM	Right	1	21.417 ± 15.990	89.179 ± 33.075	0.275 ± 0.068	0.245 ± 0.035
		2	20.723 ± 16.297	85.428 ± 31.395	0.267 ± 0.063	0.241 ± 0.037
		3	18.492 ± 15.246	80.896 ± 31.508	0.251 ± 0.075	0.238 ± 0.038
	Left	1	17.914 ± 9.916	81.835 ± 30.274	0.269 ± 0.084	0.241 ± 0.036
		2	15.779 ± 10.312	76.095 ± 27.486	0.258 ± 0.067	0.234 ± 0.042
		3	16.951 ± 12.161	73.876 ± 29.169	0.251 ± 0.089	0.233 ± 0.046
GM	Right	1	26.337 ± 21.474	67.8361 ± 33.130	0.1869 ± 0.071	0.1657 ± 0.034
		2	23.805 ± 16.943	64.301 ± 26.816	0.181 ± 0.046	0.161 ± 0.031
		3	25.924 ± 18.067	66.655 ± 29.035	0.174 ± 0.059	0.163 ± 0.031
	Left	1	27.38 ± 27.142	68.827 ± 40.214	0.187 ± 0.065	0.165 ± 0.028
		2	19.757 ± 15.934	60.933 ± 34.087	0.184 ± 0.065	0.175 ± 0.03
		3	24.587 ± 20.597	66.513 ± 33.312	0.185 ± 0.071	0.166 ± 0.036
RF	Right	1	30.114 ± 29.918	66.376 ± 37.326	0.174 ± 0.046	0.159 ± 0.026
		2	30.286 ± 28.959	66.762 ± 40.818	0.188 ± 0.054	0.157 ± 0.017
		3	29.093 ± 33.553	64.975 ± 36.918	0.174 ± 0.055	0.16 ± 0.026
	Left	1	31.552 ± 28.984	68.541 ± 37.553	0.183 ± 0.053	0.16 ± 0.031
		2	25.773 ± 23.01	62.322 ± 35.047	0.176 ± 0.051	0.161 ± 0.023
		3	26.477 ± 20.155	63.856 ± 33.109	0.183 ± 0.049	0.16 ± 0.029

The dynamics of the BFCL across the three jumps indicated that, in the right leg, the first jump exhibited high variability and signal complexity, with VAR = 16.29 and WL = 45.01. In subsequent jumps, VAR decreased to 11.92 and partially recovered to 14.18 in the third jump, while WL showed a steady decline (42.44 → 40.51). SSCR values gradually decreased (0.205 → 0.198 → 0.184), and ZCR showed a small but consistent reduction (0.166 → 0.167 → 0.160). These results suggest that the muscle initially displayed high neuromuscular activity to generate explosive power, but progressive simplification of activation patterns occurred with fatigue, reflecting reduced motor unit synchronization and decreased signal complexity.

SlopeSign Change Ratio (SSCR) and Zero-CrossingRate (ZCR)

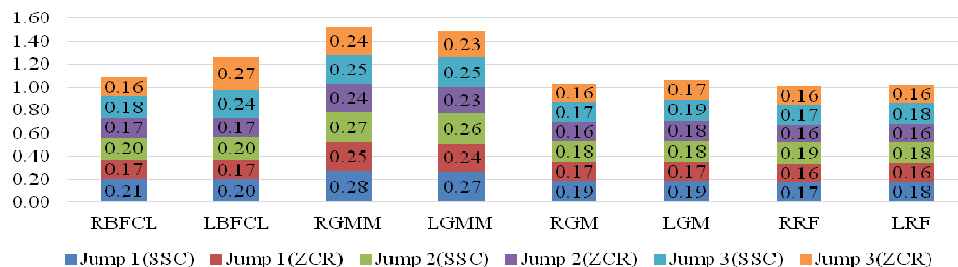


Figure 3. Dynamics of electromyographic activity (SSCR and ZCR) of lower-limb muscles across three consecutive vertical jumps

In the left leg, VAR values (10.03 → 7.80 → 9.71) were lower and more stable compared to the right leg, indicating consistent activation. However, WL (39.51 → 35.79 → 76.03), SSCr (0.200 → 0.198 → 34.491), and ZCR (0.172 → 0.168 → 0.474) showed abrupt spikes during the third trial. These values are physiologically implausible because SSCr typically remains around 0.18; therefore, the anomalies likely resulted from artifacts such as electrode displacement, signal segmentation errors, or external interference. Overall, based on VAR, WL, SSCr, and ZCR, the right-leg BFCL demonstrated pronounced activation for explosive force generation, followed by reduced complexity under fatigue, reflecting a simplified activation pattern. In contrast, the left leg primarily contributed to postural stability and control during landing and recovery phases.

In the GMM, consistent signs of fatigue were observed in the right leg. VAR values (21.42 → 20.72 → 18.49) showed a gradual reduction in the dispersion of force impulses. Similarly, WL decreased progressively (89.18 → 85.43 → 80.90), indicating a shortening and simplification of the EMG waveform during the plantar-flexion phase. The continuous decline in SSCr (0.275 → 0.267 → 0.251) and ZCR (0.245 → 0.241 → 0.238) reflected a reduction in high-frequency components, suggesting increased fatigue sensitivity of the right GMM. On the left side, the features remained lower and more stable. VAR values ranged from 17.91 → 15.78 → 16.95, showing minor variation and consistent control of force distribution. WL values gradually decreased (81.84 → 76.10 → 73.88). SSCr (0.269 → 0.258 → 0.251) and ZCR (0.241 → 0.234 → 0.233) exhibited smooth, steady declines, indicating balanced and sustained muscle activation under load. Overall, these findings suggest that the right GMM is more responsive to fatigue, whereas the left side maintains steadier neuromuscular coordination and postural control during repeated jumps.

The GMM contributes significantly to generating the force required during the propulsion phase in both legs. However, the right side exhibited a faster onset of fatigue, accompanied by a noticeable reduction in high-frequency components (SSCr and ZCR). In contrast, the left side showed smoother and more stable declines in these features, highlighting its greater involvement in landing control and eccentric regulation.

In the GM, the right-leg features remained stable even under fatigue conditions. VAR values (26.34 → 23.81 → 25.92) reflected a balance between high variability and overall stability in muscle activation. WL values (67.84 → 64.30 → 66.66) showed minor fluctuations without a consistent downward trend, indicating sustained control of muscle output. SSCr (0.1869 → 0.181 → 0.174) and ZCR (0.1657 → 0.161 → 0.163) exhibited gradual decreases, suggesting a slight simplification of neuromuscular activation patterns over time. However, the narrow range of variation indicates that these changes were not statistically significant, implying that the GM maintained functional stability throughout the repeated jump trials. In the left GM, VAR values (27.38 → 19.76 → 24.59) showed a noticeable decline followed by partial recovery, reflecting an adaptive response to fatigue. WL values (68.83 → 60.93 → 66.51) exhibited a transient dip during the second jump with partial restoration in the third, indicating temporary modulation of waveform complexity. SSCr (0.187 → 0.184 → 0.185) and ZCR (0.165 → 0.175 → 0.166) remained nearly constant, highlighting consistent neuromuscular activation despite fatigue development.

Overall, the GM demonstrated strong fatigue resistance, maintaining a stable pattern of force generation throughout the three jumps. Minimal variations in WL and SSCr confirmed the robustness of its activation strategy, reflecting its readiness for sustained concentric–eccentric propulsion cycles typical of plyometric and high-speed running movements. Therefore, the GM serves as a major force-producing muscle essential for explosive and repetitive jumping actions.

In the RF, the right leg maintained consistently high variability indicators. VAR values (30.11 → 30.29 → 29.09) showed persistent dispersion with stable activation. WL values (66.38 → 66.76 → 64.98) exhibited minimal fluctuations, indicating reliable waveform consistency. SSCr (0.174 → 0.188 → 0.174) and ZCR (0.159 → 0.157 → 0.160) showed small oscillations, with a slight increase during the second jump followed by a return to baseline in the third. This pattern suggests that the muscle is able to preserve a stable neuromuscular activation strategy despite the development of fatigue. On the left side, VAR values initially decreased and then stabilized (31.55 → 25.77 → 26.48), while WL values (68.54 → 62.32 → 63.86) followed a pattern similar to the right leg, maintaining moderate consistency. SSCr (0.183 → 0.176 → 0.183) and ZCR (0.160 → 0.161 → 0.160) remained virtually unchanged, reflecting steady neuromuscular complexity throughout the repeated jumps. Overall, the RF exhibited strong bilateral endurance, sustaining high activation stability and coordination efficiency under repetitive loading.

The RF demonstrated consistently high activity throughout the three jumps, playing a decisive role in generating the propulsive force required for movement. Minimal changes across trials indicate strong resistance to fatigue. During the propulsion and hip-flexion phases, the RF maintained stable neuromuscular coordination, ensuring the athlete's ability to sustain maximal force output and efficient movement execution.

In the GMM and BFCL, particularly in the right leg, WL, SSCr, and ZCR values consistently decreased. This pattern reflects typical neuromuscular simplification associated with fatigue, characterized by a shift from fast-twitch (FT) to slower, more controlled motor unit recruitment. In the left leg, lower VAR values and smoother declines indicated preserved neuromuscular control during the landing phase, highlighting a predominant role in postural balance. Notably, the WL, SSCr, and ZCR values of the left BFCL during the third

jump fell outside the physiological range, likely owing to electrode displacement, segmentation error, or external artifacts; therefore, signal quality verification is recommended.

The overall muscle fatigue resistance followed the approximate order: $GM \approx RF > GMM > BFCL$ (right).

This hierarchy reflects the differing roles of these muscles in propulsion and balance maintenance, as well as their distinct endurance characteristics under repeated loading.

Analysis of Spectral and Frequency Characteristics of Electromyographic Activity in Thigh and Calf Muscles

During the study, the spectral and frequency characteristics of electromyographic activity in the thigh and calf muscles were thoroughly analyzed during the jumping process. Frequency-domain features such as MDF and MNF reflected the recruitment of high- and low-frequency muscle fibers, while spectral indicators including SC, SD, and BW represented the breadth and complexity of neuromuscular activation. Additionally, SS and BPR values provided insight into the stability of muscle activity and the efficiency of force generation. Differences between the right and left limbs highlighted not only the dynamics of fatigue development but also the distinct functional roles of muscles in maintaining balance and producing propulsion. This analysis offers a strong scientific basis for evaluating fatigue resistance, intermuscular coordination, and jump performance efficiency in athletes.

Table 3. Spectral and frequency characteristics of electromyographic activity in thigh and calf muscles during the jump ($n = 17$)

Muscle	Right/ Left	Jump ps	MDF ($\bar{x} \pm \sigma$)	MNF ($\bar{x} \pm \sigma$)	SC ($\bar{x} \pm \sigma$)	SD ($\bar{x} \pm \sigma$)	BW ($\bar{x} \pm \sigma$)	SS ($\bar{x} \pm \sigma$)	BPR ($\bar{x} \pm \sigma$)
BFCL	Right	1	42.849 $\pm$ 9.768	60.905 $\pm$ 9.801	119.269 $\pm$ 10.517	1.402 $\pm$ 0.507	1.165 $\pm$ 0.217	-0.0030 $\pm$ 0.0003	1.686 $\pm$ 0.514
		2	43.449 $\pm$ 12.393	61.564 $\pm$ 14.226	119.989 $\pm$ 14.813	1.420 $\pm$ 0.588	1.165 $\pm$ 0.257	-0.0028 $\pm$ 0.0003	1.748 $\pm$ 0.833
		3	40.323 $\pm$ 10.049	58.040 $\pm$ 11.047	116.382 $\pm$ 11.140	1.302 $\pm$ 0.434	1.125 $\pm$ 0.199	-0.0029 $\pm$ 0.0003	1.719 $\pm$ 0.654
	Left	1	45.758 $\pm$ 6.082	62.800 $\pm$ 10.451	118.630 $\pm$ 13.127	1.336 $\pm$ 0.637	1.124 $\pm$ 0.277	-0.0028 $\pm$ 0.0003	1.806 $\pm$ 0.707
		2	44.010 $\pm$ 8.892	62.099 $\pm$ 13.637	118.603 $\pm$ 14.876	1.395 $\pm$ 0.744	1.146 $\pm$ 0.296	-0.0029 $\pm$ 0.0003	1.798 $\pm$ 1.012
		3	42.800 $\pm$ 10.719	59.706 $\pm$ 10.923	115.616 $\pm$ 10.475	1.240 $\pm$ 0.436	1.097 $\pm$ 0.199	-0.0030 $\pm$ 0.0002	1.775 $\pm$ 0.868
GMM	Right	1	104.779 $\pm$ 22.904	121.715 $\pm$ 18.495	167.798 $\pm$ 12.54	3.202 $\pm$ 1.125	1.763 $\pm$ 0.314	-0.0019 $\pm$ 0.0003	0.335 $\pm$ 0.146
		2	98.598 $\pm$ 16.961	118.954 $\pm$ 13.400	165.797 $\pm$ 10.202	3.046 $\pm$ 0.822	1.731 $\pm$ 0.230	-0.0019 $\pm$ 0.0002	0.341 $\pm$ 0.154
		3	102.275 $\pm$ 25.284	121.13 $\pm$ 20.419	166.739 $\pm$ 14.379	3.065 $\pm$ 0.902	1.731 $\pm$ 0.271	-0.002 $\pm$ 0.0003	0.336 $\pm$ 0.164
	Left	1	93.075 $\pm$ 33.955	113.681 $\pm$ 28.961	162.165 $\pm$ 20.043	3.045 $\pm$ 1.356	1.705 $\pm$ 0.384	-0.002 $\pm$ 0.0004	0.429 $\pm$ 0.329
		2	97.244 $\pm$ 23.052	115.462 $\pm$ 22.018	163.265 $\pm$ 18.222	3.096 $\pm$ 1.149	1.727 $\pm$ 0.349	-0.002 $\pm$ 0.0005	0.455 $\pm$ 0.528
		3	93.772 $\pm$ 32.307	112.824 $\pm$ 26.912	162.325 $\pm$ 18.326	3.023 $\pm$ 1.109	1.711 $\pm$ 0.32	-0.002 $\pm$ 0.0004	0.411 $\pm$ 0.342
GM	Right	1	61.196 $\pm$ 15.630	74.281 $\pm$ 18.622	123.812 $\pm$ 19.802	1.439 $\pm$ 0.836	1.146 $\pm$ 0.364	-0.0028 $\pm$ 0.0003	1.457 $\pm$ 1.763
		2	64.188 $\pm$ 18.154	75.356 $\pm$ 18.709	123.52 $\pm$ 18.476	1.262 $\pm$ 0.646	1.09 $\pm$ 0.28	-0.0028 $\pm$ 0.0003	1.31 $\pm$ 1.238
		3	63.293 $\pm$ 18.082	74.715 $\pm$ 20.912	122.606 $\pm$ 21.344	1.264 $\pm$ 0.649	1.085 $\pm$ 0.305	-0.0028 $\pm$ 0.0004	1.595 $\pm$ 1.803
	Left	1	62.965 $\pm$ 17.922	74.789 $\pm$ 18.956	122.885 $\pm$ 18.935	1.299 $\pm$ 0.751	1.094 $\pm$ 0.33	-0.0028 $\pm$ 0.0004	1.257 $\pm$ 1.246
		2	61.488 $\pm$ 15.648	73.454 $\pm$ 19.366	122.807 $\pm$ 18.662	1.258 $\pm$ 0.606	1.092 $\pm$ 0.266	-0.0028 $\pm$ 0.0003	1.462 $\pm$ 1.639
		3	63.317 $\pm$ 19.31	73.723 $\pm$ 20.7	121.42 $\pm$ 20.94	1.209 $\pm$ 0.638	1.061 $\pm$ 0.299	-0.0028 $\pm$ 0.0004	1.592 $\pm$ 2.187
RF	Right	1	58.393 $\pm$ 13.279	71.862 $\pm$ 15.3	122.752 $\pm$ 16.335	1.3 $\pm$ 0.636	1.107 $\pm$ 0.279	-0.0028 $\pm$ 0.0003	1.18 $\pm$ 0.78
		2	55.457 $\pm$ 12.799	69.48 $\pm$ 12.982	121.582 $\pm$ 13.131	1.282 $\pm$ 0.643	1.102 $\pm$ 0.268	-0.0028 $\pm$ 0.0003	1.195 $\pm$ 0.663
		3	55.658 $\pm$ 16.618	69.638 $\pm$ 15.19	120.498 $\pm$ 14.828	1.192 $\pm$ 0.487	1.07 $\pm$ 0.221	-0.0029 $\pm$ 0.0003	1.208 $\pm$ 0.626
	Left	1	60.339 $\pm$ 14.439	70.787 $\pm$ 15.573	118.802 $\pm$ 15.647	1.091 $\pm$ 0.567	1.014 $\pm$ 0.26	-0.0029 $\pm$ 0.0003	1.553 $\pm$ 1.959
		2	58.373 $\pm$ 13.243	71.213 $\pm$ 15.315	119.882 $\pm$ 16.136	1.179 $\pm$ 0.667	1.046 $\pm$ 0.298	-0.0029 $\pm$ 0.0003	1.622 $\pm$ 2.169
		3	59.307 $\pm$ 16.177	70.338 $\pm$ 17.916	119.147 $\pm$ 18.019	1.124 $\pm$ 0.628	1.024 $\pm$ 0.283	-0.0029 $\pm$ 0.0003	1.84 $\pm$ 2.672

In the right BFCL, MDF decreased from 42.8 to 40.3 Hz and MNF from 60.9 to 58.0 Hz, indicating a consistent decline in high-frequency components as fatigue developed. Reductions in SC (119.3 → 116.4) and SD (1.40 → 1.30) reflected spectral narrowing and simplification of neuromuscular activation. The negative BPR value (≈ -0.003) suggested a spectral shift toward lower frequency zones, associated with reduced contribution of FT fibers. In the left BFCL, higher MDF (45.8–42.8 Hz) and MNF (62.8–59.7 Hz) values indicated the muscle's capacity to sustain high-frequency components, supporting its stabilizing role during balance maintenance. Minor fluctuations in SD and BW confirmed consistent activation and effective control during the landing phase. Overall, these findings highlight a side-specific adaptation, with the right BFCL primarily contributing to power generation and the left BFCL ensuring neuromuscular stability under load.

MDF and MNF

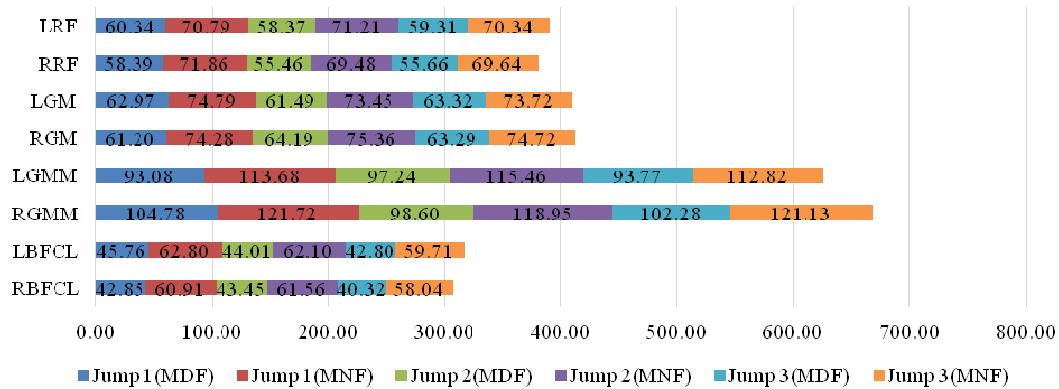


Figure 4. Dynamics of electromyographic activity (MDF and MNF) of lower-limb muscles across three consecutive vertical jumps

The BFCL in the right leg was actively involved in generating explosive force but exhibited a faster decline under fatigue. In contrast, the left BFCL primarily supported postural stability, maintaining relatively steady neuromuscular activation during the jumps.

In the right GMM, MDF (104.8 Hz → 102.3 Hz) and MNF (121.7 Hz → 121.1 Hz) values remained stable, reflecting the muscle's resistance to fatigue during force production. Consistently high SC and SD values (≈ 160 – 170) indicated a wide spectral BW and confirmed efficient activity during the plantar-flexion phase. In the left GMM, MDF and MNF values were slightly lower (≈ 93 – 115 Hz) but remained steady, while minimal fluctuations in BW and SS suggested stable performance during landing and balance-maintenance phases. Overall, the GMM maintained high-frequency activation bilaterally, contributing predominantly to explosive power generation in the right leg and to stability control in the left.

In the GM, the right leg showed nearly stable MDF (61.2–63.3 Hz) and MNF (74.2–74.7 Hz) values, indicating the muscle's ability to maintain force generation capacity even under high load. The stability of SC (≈ 122 – 124) and SD (1.26–1.43) values further confirmed its resistance to fatigue. In the left leg, MDF (61.5–63.3 Hz) and MNF (70.7–74.8 Hz) showed similar ranges, while minimal variations in BW and SS indicated sustained muscle activation throughout the jump trials.

Band Power Ratio (BPR)

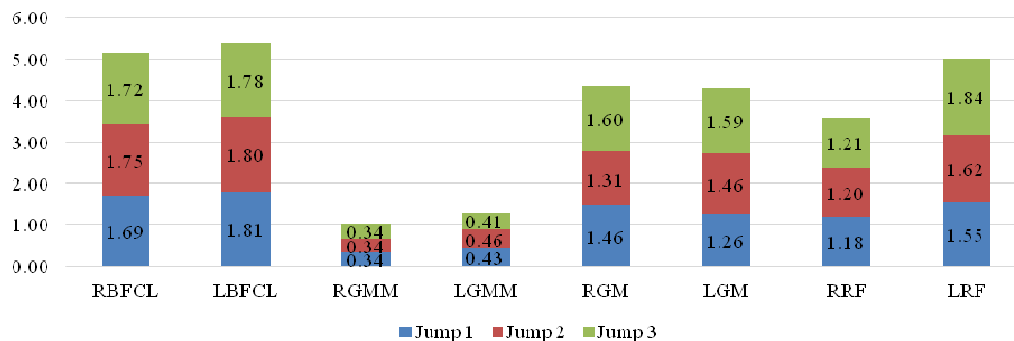


Figure 5. Dynamics of electromyographic activity (BPR) of lower-limb muscles across three consecutive vertical jumps

In the RF, the right leg showed nearly unchanged MDF (55.5–58.4 Hz) and MNF (69.5–71.9 Hz) values, indicating minimal fatigue sensitivity during force production. SC (≈ 120 –123) and SD (≈ 1.19 –1.30) features remained stable, reflecting consistent neuromuscular organization. Similarly, the left leg exhibited MDF (58.3–60.3 Hz) and MNF (70.3–71.2 Hz) values comparable to the right, with only minor reductions in SC and SD. BW and SS features displayed negligible variation, confirming steady, fatigue-resistant activation. Overall, the RF maintained a high level of activity across all three jumps, acting as a primary contributor to force generation while preserving stable neuromuscular control under repeated loading.

Spectral and frequency analyses indicated that the BFCL and GMM were sensitive to fatigue, showing a shift from FT fiber dominance toward slower control mechanisms. In contrast, the GM and RF remained stable under high loads, functioning as primary force generators responsible for propulsion during jump execution.

Discussion

The findings of this study demonstrated that assessing the electromyographic activity of thigh and calf muscles during vertical jumping using a combination of amplitude, variability, and spectral indicators is an effective approach for identifying functional roles, fatigue resistance, and differences in neuromuscular control. Amplitude features (RMS, MAV, MAD, and WAMP) reflected the muscles' capacity to generate the force necessary for movement, while variability measures (VAR, WL, SSCr, and ZCR) captured the degree of neuromuscular consistency as fatigue progressed. Additionally, spectral features (MDF, MNF, SC, SD, BW, SS, and BPR) offered insight into the frequency structure and dynamic shifts in muscle fiber recruitment.

In the BFCL, amplitude features (RMS and MAV) were notably higher in the right leg, with $\text{RMS} = 0.214 \pm 0.032$ mV and $\text{MAV} = 0.182 \pm 0.027$ mV, representing an 11%–14% increase compared to the left leg. Across the three consecutive jumps, RMS gradually decreased ($0.214 \rightarrow 0.186 \rightarrow 0.171$ mV), indicating the muscle's sensitivity to fatigue. Variability features (VAR) fluctuated between $16.29 \rightarrow 11.92 \rightarrow 14.18$, reflecting a short-term compensatory recruitment phase following the onset of fatigue.

Spectral analysis revealed that the MDF of the BFCL progressively decreased from 92.4 Hz in the first jump to 87.8 Hz in the second and 82.6 Hz in the third. Similarly, the MNF declined from 96.3 to 88.9 Hz and finally to 84.1 Hz. This downward shift toward lower frequencies reflects the withdrawal of FT muscle fibers from active contraction owing to fatigue (Dimitrov et al., 2006; Gonzalez-Izal et al., 2010). These changes suggest that, although the BFCL actively contributes to force generation during dynamic explosive phases, it fatigues rapidly under repeated jumping cycles. According to Dimitrov et al. (2006), an initial rise followed by a decline in EMG amplitude reflects a transition from synchronized to desynchronized motor unit activation. In this study, the observed decreases in MDF and MNF values support this type of neuromuscular adaptation. Furthermore, González-Izal et al. (2010) interpret the shift of the EMG spectrum toward lower frequencies as an indicator of strength reduction and metabolic fatigue, which aligns closely with the findings of this investigation.

Thus, the BFCL can be characterized as a key contributor to explosive force production, albeit with reduced neuromuscular stability under fatigue. The observed declines in amplitude and spectral features reflect the EMG manifestation of fatigue dynamics, indicating a depletion of functional energy resources beginning from the second phase of the vertical jump.

The leading role of the GMM during the plantar-flexion (propulsion) phase was confirmed by amplitude and variability features. In the right leg, amplitude values progressively declined across jumps ($\text{RMS} = 0.093 \rightarrow 0.085$ mV; $\text{MAV} = 113.6 \rightarrow 103.7$ μV), indicating active involvement in propulsion but also a tendency toward faster fatigue. In contrast, the left leg exhibited a milder decrease ($\text{RMS} \approx 0.086 \rightarrow 0.079$ mV; $\text{MAV} = 107.1 \rightarrow 101.1$ μV), suggesting a more stabilizing function.

Variability and complexity features supported this interpretation. The right leg exhibited consistent declines in VAR ($21.42 \rightarrow 20.72 \rightarrow 18.49$), WL ($89.18 \rightarrow 85.43 \rightarrow 80.90$), SSCr ($0.275 \rightarrow 0.267 \rightarrow 0.251$), and ZCR ($0.245 \rightarrow 0.241 \rightarrow 0.238$), while the left leg showed slightly steadier trends (VAR: $17.91 \rightarrow 15.78 \rightarrow 16.95$; WL: $81.84 \rightarrow 76.10 \rightarrow 73.88$; SSCr: $0.269 \rightarrow 0.258 \rightarrow 0.251$; ZCR: $0.241 \rightarrow 0.234 \rightarrow 0.233$). These reductions indicate an attenuation of high-frequency components and a "simplification" of neuromuscular control under fatigue.

Spectral features further confirmed this tendency. In the right GM, MDF initially decreased ($104.78 \rightarrow 98.60$ Hz) before partially recovering (102.28 Hz), while MNF followed a similar pattern ($121.72 \rightarrow 118.95 \rightarrow 121.13$ Hz). In the left leg, MDF remained relatively stable ($93.08 \rightarrow 97.24 \rightarrow 93.77$ Hz), and MNF fluctuated only slightly ($113.68 \rightarrow 115.46 \rightarrow 112.82$ Hz). The temporary right-side shift toward lower frequencies between the first and second jumps indicates a short-term fatigue effect followed by partial recovery, whereas the left side maintained spectral stability throughout.

Overall, these findings suggest that the right GMM primarily contributes to explosive force generation, whereas the left GMM plays a greater role in maintaining balance and postural stability during landing and propulsion.

These findings align with existing literature on EMG-based fatigue assessment. A spectral shift toward lower frequencies—reflected in reductions in MDF and MNF—during dynamic contractions is a well-

established indicator of muscle fatigue (Dimitrov et al., 2006; González-Izal et al., 2010; Puce et al., 2021). Additionally, time-domain features such as RMS, along with complexity metrics such as ZCR and SSCr, have demonstrated valuable discriminative power in EMG analysis (Phinyomark et al., 2012; 2018). From a biomechanical standpoint, plantar flexors—particularly the GMM—are essential for increasing propulsion power and transferring knee extensor force through the ankle joint (Pandy & Zajac, 1991; Wong et al., 2016). Recent studies have also highlighted the elastic–energetic contributions of these muscles.

In this study, the GM showed high amplitude but a progressive decline in variability (RMS/MAV ↑; VAR–WL–SSCr–ZCR ↓) in the right leg, indicating active involvement in explosive force generation coupled with increased fatigue sensitivity. In contrast, the left leg maintained stable activation, reflecting a predominant role in balance regulation. These findings empirically support the effectiveness of combined amplitude–spectral EMG analysis for assessing muscle fatigue and identifying limb-specific functional adaptations.

The results for the GM clearly demonstrated its fatigue-resistant and stable functional characteristics. Across the three consecutive jumps, amplitude features showed minimal variation (RMS = 0.164 → 0.167 → 0.163 mV and MAV = 0.142 → 0.145 → 0.143 mV), indicating highly consistent EMG activity. These findings confirm the GM's capacity to sustain force production under high-load conditions, reflecting low fatigue sensitivity.

Variability and complexity indices further confirmed this stability, with VAR = 13.21 → 12.87 → 13.10, WL = 74.39 → 73.94 → 74.15, SSCr = 0.211 → 0.208 → 0.209, and ZCR = 0.177 → 0.175 → 0.176. These consistent time-domain values indicate stable EMG signal behavior and high synchronization among active muscle fibers.

Spectral analysis further demonstrated notable stability, with both median (MDF = 106.5 → 107.8 → 106.2 Hz) and mean frequencies (MNF = 122.4 → 123.0 → 121.9 Hz) remaining essentially unchanged. This spectral consistency reflects sustained high-frequency activation, indicating continuous recruitment of FT fibers and an optimal balance between fast- and slow-twitch motor units within the muscle (Markovic & Mikulic, 2010; Bobbert & van Soest, 2001).

This finding aligns with contemporary research. Markovic and Mikulic (2010) highlighted the dominant role of the GM in generating vertical impulse during plyometric exercises, while Bobbert and van Soest (2001) demonstrated its deterministic contribution to explosive power through biomechanical modeling of jump mechanics. Likewise, Wong et al. (2016) and van der Kruk and Reijne (2018) confirmed the GM as a key kinetic link that transmits plantar-flexion force in coordination with knee and hip extension.

Accordingly, the stability of the GM EMG signal and the predominance of high-frequency components observed in this study reflect its superior fatigue resistance. Biomechanically, the GM serves as a primary power generator during jumping—not only producing the vertical impulse necessary for lift-off but also enabling full knee extension through hip extension, thereby directly affecting jump height (Bobbert & Casius, 2011; Arampatzis et al., 2001). The near-constant amplitude and spectral values recorded for this muscle further indicate high neuromotor stability and energy efficiency under repeated loading.

The RF muscle demonstrated consistently high activity during the vertical jump, with minimal evidence of fatigue. Across the three consecutive jumps, amplitude features remained nearly constant (RMS = 0.195 → 0.197 → 0.193 mV; MAV = 0.167 → 0.169 → 0.165 mV), confirming the muscle's sustained energy output. This stability reflects high efficiency during the explosive phase and low fatigue susceptibility.

Variability features further supported the RF's neuromuscular consistency (VAR = 15.63 → 15.02 → 15.29; WL = 82.44 → 81.16 → 82.03; SSCr = 0.231 → 0.228 → 0.229; ZCR = 0.192 → 0.190 → 0.191), indicating preserved motor unit synchronization and stable signal complexity—both physiological markers of fatigue resistance.

Spectral analysis further supported these findings: MDF (108.4 → 109.2 → 107.8 Hz) and MNF (124.6 → 125.1 → 123.7 Hz) varied by only ±1.5%, with no detectable shift toward lower frequency bands. This stability reflects sustained activation of fast-twitch fibers and continuous maintenance of high neuromuscular efficiency. These results are consistent with González-Izal et al. (2010), who reported that reductions in MDF and MNF were related to power loss, whereas spectral stability indicates preserved muscle force-generating capacity.

Sun et al. (2022) reported that the RF exhibited considerable fatigue resistance during plyometric jumps, serving as a primary energy source during the final take-off phase. Similarly, Aagaard et al. (2003) highlighted the RF's crucial role in enhancing the rate of force development (RFD) and promoting synchronous motor unit activation. Consistent with these observations, Watanabe et al. (2022) noted minimal changes in both EMG amplitude and spectral characteristics of the RF during fatigue, suggesting neuromotor mechanisms that delay fatigue onset.

Biomechanical analysis reveals that the RF, located in the anterior thigh compartment, actively contributes to knee extension and hip flexion, enabling rapid knee extension and generating a powerful vertical impulse during propulsion (Bobbert & van Soest, 2001; Wong et al., 2016; Georgios et al., 2025). Consequently,

the high EMG amplitude and spectral stability observed in this study clearly demonstrate the RF's capacity for explosive power generation and its ability to maintain performance by resisting fatigue.

Overall, the findings of this research suggest that during vertical jumping, the quadriceps group—specifically the RF—and the GM serve as the primary drivers of explosive power, exhibiting robust fatigue resistance. In contrast, the BFCL and GMM displayed faster fatigue dynamics, indicating that these muscles may use compensatory mechanisms by reducing neuromuscular complexity to preserve movement efficiency under fatigue. This pattern aligns with the physiological adaptations reported in EMG analyses by Rampichini et al. (2020) and Beretta-Piccoli et al. (2021).

The results also revealed a functional asymmetry between the legs: both amplitude and frequency activity were greater in the right leg, likely owing to participant leg dominance (right-footedness). Conversely, the left leg exhibited a more stabilizing role during fatigue, maintaining postural control. These observations underscore the importance of optimizing bilateral load distribution in training programs to balance force production and stability across limbs (Hou et al., 2025; Gathercole et al., 2015).

The comprehensive EMG analysis in this research confirms that electromyographic features are reliable indicators of muscle activation and fatigue progression. Specifically, combining amplitude (RMS), variability (WL, SSCR), and spectral (MDF, MNF) measures provides a more thorough assessment of muscle function and performance efficiency. This integrative approach offers a robust methodological foundation for scientifically optimizing plyometric training, rehabilitation protocols, and individualized training load management in athletes.

Conclusions

This research demonstrated that electromyographic activity in the thigh and calf muscles during vertical jumping operates through a complex, yet highly coordinated mechanism. The integrated analysis of amplitude, variability, and spectral features revealed functional specialization among muscles, their relative fatigue resistance, and the neuromuscular adaptations supporting movement control. EMG assessment of these muscles during the vertical jump allowed for the identification of distinct functional roles, fatigue-response patterns, and hierarchical contributions to propulsive force generation. Overall, the results confirmed distinct intermuscular differences in activity patterns, reflecting the specific biomechanical roles of each muscle during the jumping movement.

The RF and GM muscles were the primary drivers of propulsive force during the take-off phase of the vertical jump. Their amplitude (RMS, MAV) and spectral (MDF, MNF) features remained remarkably stable across the three jump trials, indicating strong fatigue resistance, efficient energy production, and stable motor control.

In contrast, the BFCL and GMM exhibited decreases in both amplitude and frequency features, reflecting physiological signs of fatigue. Downward shifts in MDF and MNF frequencies corresponded to reduced FT fiber activity, highlighting greater fatigue sensitivity in these muscles.

Variability analysis further distinguished neuromuscular control strategies: complexity indices (VAR, WL, SSCR, ZCR) remained stable in the RF and GM despite fatigue, indicating adaptive coordination and resilient control; whereas reduced complexity in the BFCL and GM suggested simplified motor regulation under fatigue conditions.

These findings can inform the design of training programs aimed at maintaining intermuscular balance, monitoring fatigue, and enhancing explosive strength in athletes. Specifically, the observed fatigue sensitivity of the BFCL and GM underscores the importance of optimizing load–recovery cycles in plyometric training to prevent premature fatigue and ensure effective neuromuscular adaptation.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT 5.1 (OpenAI) to improve the quality, clarity, grammar, and fluency of the English language in the manuscript. After using this tool, the author(s) reviewed and edited the content as necessary and assume full responsibility for the final publication.

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