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Inter-limb neuromuscular activity of the gastrocnemius muscle during unilateral and bilateral explosive jumps and relationship with jump performance

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ABSTRACT

Understanding the neuromuscular demands of explosive tasks is essential for enhancing performance and reducing injury risk. This study analyzed inter-limb activation of the medial and lateral gastrocnemius during take-off and landing phases of bilateral and unilateral countermovement jumps (CMJ) and horizontal jumps (HJ), examining its relationship with inter-limb asymmetry and performance. Twenty-six physically active participants performed CMJ and HJ tasks while bilateral surface electromyography was recorded from both gastrocnemius heads. Jump performance was evaluated using flight time (CMJ) and distance (HJ), and asymmetry indices were computed between dominant and non-dominant limbs. Results showed significantly greater muscle activity during take-off than landing across all conditions ($p < 0.05$). During CMJ landings, the medial gastrocnemius was more active than the lateral, with no activation differences found between unilateral and bilateral jumps. A moderate positive correlation was observed between CMJ performance and bilateral take-off asymmetry ($r = 0.43$, $p = 0.02$). Conversely, greater activation in the non-dominant gastrocnemius was negatively associated with performance in both CMJ and HJ ($r = -0.39$ to -0.48, $p < 0.05$). In conclusion, gastrocnemius muscles display phase-specific activation patterns. Moderate asymmetry during take-off may benefit performance, while excessive activation in the non-dominant limb may reflect compensatory strategies detrimental to jump efficiency.

1. Introduction

Humans tend to preferentially use one limb over the contralateral one, a phenomenon known as lateral dominance, which can contribute to functional asymmetries (Carpes et al., 2010). Interlimb asymmetries have been a popular source of investigation, particularly to provide insight into athletic performance, injury prevention, and rehabilitation (Fox et al., 2023; Guan et al., 2022; Jordan and Bishop, 2024; Pappas and Carpes, 2012). To determine interlimb asymmetries in strength, functional performance tests, such as jumping tests, have been proposed as valid and reliable field-based alternatives to single-joint strength measurements performed on an isokinetic dynamometer (Bishop et al., 2018). These tests not only offer an assessment that parallels the dynamic closed-chain movements experienced in sport and incorporates the stretch–shortening cycle, but they are also easy to implement in clinical and field settings (Bishop et al., 2017). Despite the advantages of using jumps as dynamic functional assessments, it is essential to highlight that they can be influenced by movement coordination and balance (Benjanuvatra et al., 2013; Impellizzeri et al., 2007). Factors such as jumping direction (vertical vs. horizontal), type of jump (unilateral vs.

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bilateral), or phases of a jump (take-off vs. landing) may affect the strength, balance, and coordination requirements (Cao et al., 2024; Kotsifaki et al., 2021).

Previous studies have used bilateral and unilateral procedures to assess strength asymmetry (Bishop et al., 2018). In this regard, unilateral tests may be the preferred option for quantifying interlimb differences due to their enhanced sensitivity in detecting asymmetries, which may be partly attributed to the heightened instability associated with single-leg tests (Benjanuvatra et al., 2013). In the sports setting, the gastrocnemius (GA) muscle serves as the primary generator of power output for running and jumping movements, and it is a key muscle for ankle stability during vertical jumps (Ebben et al., 2009). Therefore, it is a relevant muscle for generating explosive ankle movements and maintaining knee stability during landing and braking actions (Werkhausen et al., 2021). Research demonstrates a significant relationship between GA strength and jump performance. Kadlubowski et al. (2024) emphasised the need to include plantar flexor exercises in strength and conditioning programs to enhance high-intensity actions involving fast stretch–-shortening cycles. Additionally, resting medial gastrocnemius (MG) stiffness has been positively correlated with drop jump height and efficiency (Ando et al., 2021). Lower-body muscle architecture, particularly the lateral gastrocnemius (LG) pennation angle, has been identified as a strong predictor of jump height and power across various jump types (Secomb et al., 2015). These findings highlight the importance of developing GA strength to enhance jump performance.

Despite the great importance of GA during jump, most studies surrounding electromyography (EMG) analysis have been conducted in knee flexors and extensors at landing, due to their relationship with non-contact anterior cruciate ligament injuries (Larwa et al., 2021). Moreover, the literature that had evaluated muscular activity during jumping tests on GA, present some limitations such as measuring only one of the two bellies (Howard et al., 2015; Klyne et al., 2012; Mackala et al., 2013; Walsh et al., 2012; Wulf et al., 2010), measuring only one leg (Davison et al., 2016; Fletcher, 2010; Sozbir, 2016) or providing data from the whole jump instead of differencing by jump phases (i.e. take-off vs. landing) (Davison et al., 2016; Fletcher, 2010; Mackala et al., 2013; Sozbir, 2016). Given the potential implications of assessing interlimb asymmetries for athletes and individuals with specific pathologies, it is essential to understand the activation of GA and bilateral asymmetries in a group of healthy and physically active participants during the most common vertical and horizontal jumps (e.g., countermovement jump (CMJ), horizontal jump (HJ)).

Therefore, the primary aim of this study was to determine the differences in GA muscular activity at the take-off and landing phases of bilateral and unilateral jumps. A secondary aim was to determine the relationship between lower-limb asymmetry and performance, as well as the correlation between GA muscular activity and the take-off and landing phases during CMJ and HJ performance. Based on previous reference literature, the following formal hypotheses are proposed: GA EMG activity will be significantly higher during the take-off phase compared to the landing across all jump conditions, and a positive correlation is expected between inter-limb asymmetry indices and jump performance. This research has significance for coaches, practitioners, and clinicians, as it will describe natural bilateral asymmetries in GA activity during the most common vertical and horizontal jumps. Furthermore, it will show whether GA muscular activity during take-off jumps influences jump performance, guiding conditioning and rehabilitation programs.

2. Methods

2.1. Experimental design

This research used a quasi-experimental design in which a comparison of the maximum EMG activation of the GA muscles (LG and MG) from both legs, normalized by the maximum activation of each muscle in a maximal sprint, was conducted in two different explosive jumps (i.e., CMJ and HJ) performed bilaterally and unilaterally.

Participants were informed both verbally and in writing about the procedures, potential risks, and benefits of the tests, and they provided written consent before the commencement of the study. The experimental procedures were approved by the Ethics Committee of the University of Valencia (1973315) and were conducted following the latest revision of the Declaration of Helsinki.

2.2. Participants

The study included 26 physically active participants (19 males and 7 females) (mean (SD) age of 25 (5) years; body mass of 68.4 (11.9) kg and height of 1.7 (0.1) m). They had experience with strength training and running (> 2 years). All participants had normal or corrected-to-normal vision (using glasses or contact lenses if necessary), which is a standard condition for participation in physical performance studies and was not considered a specific exclusion factor. The dominant lower limb of all participants was the right leg, except for one of them. The dominant leg was determined by asking the question, *"If you would kick a ball on a target, which leg would you use to kick the ball?"* (van Melick et al., 2017). Exclusion criteria included a history of GA injury (i.e., complete or partial muscle rupture, any contusion, and/or tendon injury), any lower extremity/low-back injuries, acute or chronic pain in the lower body or low back, neurological or vestibular disease, and any exercise contraindication. Participants were asked to avoid any strength or running training for 48 h before testing.

2.3. Procedures

This study employed a single session, including familiarisation and experimental procedures. The warm-up and the jump measurements were performed in a laboratory setting, under standard artificial laboratory lighting, ensuring a consistent and well-lit environment. The sprints were performed on an artificial turf field during daylight hours with natural light. Participants performed all tests with their usual running shoes. Familiarisation with tests was performed during the warm-up, as they were common exercises. The warm-up consisted of a 5 min period at a self-perceived comfortable pace. Participants then performed dynamic stretches for approximately 3 min (including 3 repetitions for all muscles involved) and one set of 8 repetitions of full squat and long jump exercises with a progressive increase in the level of effort. These sub-maximal trials were conducted to act as test familiarization. It concluded with 2 x 50 m submaximal runs, approximately 80 % of maximum perceived sprint speed. No additional practice trials were performed for the sprints beyond these sub-maximal runs.

After the warm-up, participants rested for 5 min before performing one of the six explosive exercises. The six exercises included the CMJ and HJ performed bilaterally and unilaterally in each leg (i.e., dominant and non-dominant). To minimise the effects of the sequence of the exercises, the order of the exercises was determined through simple randomisation. A simple coin toss was used to determine which exercise (CMJ or HJ) would be performed first (*a priori,* "heads" was designated the CMJ and "tails" the HJ). Next, participants chosen from a deck of shuffled cards to determine the order of bilateral or unilateral (i.e., dominant and non-dominant). The participants received a visual demonstration of each movement before the first trial, after which they performed the exercise. This initial performance for each of the six jump conditions served as one specific practice trial to ensure familiarity with that particular movement pattern before data collection began.

Participants' body mass was measured to the nearest 0.1 kg using an electronic scale (TANITA BC 730, TANITA Corp., Arlington Heights, IL, USA), and body height was measured with a stadiometer (FISAUDE Instruments Ltd., Madrid, Spain) to the nearest 1 cm. For CMJ performance calculations, the leg length and height with bended knees at about 90° were measured using a measuring tape to the nearest 1 cm and a goniometer. Leg length was measured from the trochanter to the distal part of the shoe in the lying position. Height at 90° knees bent was measured vertically from the trochanter to the ground in an optimal jump performance position.

2.4. Countermovement jump

The bilateral CMJ starting position was standing with a straight torso and knees fully extended, with the feet shoulder-width apart. Participants were asked to keep their hands on their waists throughout the whole jump. They were instructed to perform a quick downward movement (approximately 90° of knee flexion) and a fast-upward movement to jump as high as possible.

All jumps were performed on a hardwood surface and initiated by executing a countermovement to a self-selected depth before accelerating vertically as quickly as possible. The jumping legs had to remain fully extended during the flight phase, with hands placed to the hips throughout the jump before landing back on the floor.

The unilateral CMJ was performed under the same premises. The starting position was a one-leg standing position with the knee fully extended and a straight torso. The non-jumping leg started slightly flexed at the hip and knee joints, so that the foot would hover approximately parallel with the medial malleolus of the jumping leg.

A digital camera was positioned at 4 m and 20 cm above the floor and recorded all CMJ jumps. The My Jump 2 app was used to measure the jump height performance variable. Jump height was calculated from flight time, that is, the time between take-off and ground contact. My Jump 2 app for measuring vertical jump height has been previously validated (Bogataj et al., 2020; Gençoğlu et al., 2023). The CMJ was considered successful if the participant could perform the jump with approximately 90° knee flexion, maintaining the landing for at least two seconds with their hands still on their hips.

2.5. Horizontal jumps

For the bilateral HJ, participants were instructed to stand on both legs with the feet shoulder-width apart and hands placed to their hips. Participants were asked to hop as far as possible in the forward direction and land on both feet. For the unilateral HJ, participants were instructed to stand on the leg to be tested, hop as far as possible in the forward direction, and land on the same leg. There was no standardization for positioning the uninvolved leg to ensure a more natural movement pattern (Hardesty et al., 2017). The total hop distance was measured from the line drawn on the floor to the rear part of the running shoe at the point of landing. The outcome measure was the best performance (maximum distance to the nearest cm) of the two test trials.

The same examiner graded all tests. All jumps were considered successful if the participant could maintain the landing for at least two seconds with the hands still on the hips. Unilateral jumps were considered unsuccessful when the participant touched the floor with the contralateral lower or upper extremities, lost balance, or needed an additional short hop after the initial landing (Reid et al., 2007). After a failed trial, participants were allowed to make a new attempt (Reid et al., 2007). The number of failed attempts before obtaining the two valid jumps did not exceed two additional repetitions for each jump type and leg. The first 2 valid jumps of each type (bilateral and unilateral (i.e., dominant and non-dominant)) were selected and included for further analysis. The rest time between each jump was 60 s, and 2 min between the different jump types (i.e., bilateral CMJ, unilateral dominant CMJ, unilateral non-dominant CMJ, bilateral HJ, unilateral dominant HJ, and unilateral non-dominant HJ).

2.6. Sprints

Two maximal 40 m sprints were performed after the jumping tests (Pinniger et al., 2000). Participants started in a standing position, with one leg in front of the other, their body weight on the front leg, and their trunk slightly bent forward. An audible signal was used to start the sprint. Participants ran with their usual running shoes. They were instructed to run as fast as they could the 40 m distance and at wind speeds less than 8 km/h (Fitzsimons et al., 1993). A 5 min rest was applied between sprints. To prevent losing the EMG signal with the mobile device, the researcher stood 10 m from the start and, once the participant passed in front of him, ran alongside the participant until the end of the sprint. This procedure ensured that the distance between the transmitting devices and the Samsung Galaxy receiving device was consistently maintained within an effective operational range, approximately 10 m, which successfully prevented any loss of EMG signal during data collection. This strategy proved successful, and as a result, no loss of EMG signal was experienced during data collection.

2.7. EMG measurements

EMG activity (mV) was recorded for each leg's MG and LG muscles. Two synchronized, portable, 2-channel devices, coupled with an inertial sensor from the Shimmer branch (Realtime Technologies Ltd., Dublin, Ireland), featuring a 16-bit analogue-to-digital (A/D) conversion, were used. No external voltage amplification (e.g., ×1000) was applied to the signal. However, the combination of high-resolution A/D conversion and subsequent robust digital filtering ensured reliable signal acquisition. The devices were attached to the anterior border of the tibia of each leg. The sampling frequency was programmed at 1024 Hz. These devices transmitted the raw EMG signals wirelessly to the main acquisition unit.

The EMG signal was monitored using the mDurance software (MDurance Solutions S.L., Granada, Spain) for Android, which had been previously validated (Molina-Molina et al., 2020), and stored on a cloud-coded server for further analysis. The application was installed on a Samsung Galaxy device, model M13, with the Android 10 operating system version (Samsung Group, Seoul, South Korea).

The MDurance software digitally filtered the raw signals automatically through a Butterworth band-pass filter of the fourth order, between 20 and 450 Hz. A high-pass cutoff frequency of 20 Hz was employed to reduce any artifacts that might occur throughout the movement, to have a negligible impact on the total power recorded by the EMG (Ferri-Caruana et al., 2022).

All tests were recorded, and sensor allocation was conducted prior to the warm-up. First of all, the skin was shaved, rubbed, and cleaned with alcohol. Bipolar pre-gelled Ag/AgCl surface electrodes (MedCaT B.V. Doorndistel, Spain, Europe) were then used to record the EMG from these muscles. They were placed in pairs 1.5–2 cm apart and parallel to the muscle fibres. Electrode placement to collect EMG signals from the selected muscles was set following the SENIAM guidelines (Hermens et al., 1999). The maximum EMG amplitude (peak EMG) of each muscle during the entire sprint was obtained from the two sprints, and the mean of the two maximum values (throughout all the sprints) was used for subsequent normalization of the maximum EMG amplitude obtained in each test. Thus, the maximum EMG amplitude in each test was expressed as a percentage of the maximum EMG amplitude during the sprint. This normalization method was chosen primarily for its functional relevance and ecological validity. Sprints are maximal, dynamic, and explosive tasks that heavily involve the gastrocnemius muscle, similar to the jumps being investigated. This provides a reference point that is functionally analogous to the explosive nature of the jump tasks. Maximal 40 m sprints, as performed by the physically active participants, are expected to elicit maximal or near-maximal GA activation in a demanding, multi-joint, and propulsive motor task, offering a robust and representative peak activation reference relevant to athletic performance. Unlike static maximal voluntary isometric contractions (MVCs), dynamic sprints better reflect the muscle's activation capacity during complex movements involving the stretch–shortening cycle, avoiding the challenges of achieving a true maximal isometric contraction for a multi-joint muscle like the gastrocnemius in an isolated, static setting.

The peak mean GA EMG activity was calculated as the average peak EMG activity obtained at LG and MG. The root mean square (RMS) was calculated from a window showing the duration of the movement. Fig. 1 shows one participant's example of the dominant and non-dominant LG and MG electromyographic activity during the bipodal HJ.

2.8. Inter-Limb asymmetry Calculation

Although several options have been proposed to calculate lower limb asymmetry (Bishop et al., 2016), the purpose of the present analyses was to focus on the variability of the GA muscular activation between-limb differences; therefore, the main concern was the absolute difference between the mean GA activity of the lower limbs for each variable, and was calculated as follows:

$$\textit{Lower-Limb Difference Score} = |(\textit{Dominant} - \textit{Non-dominant})|$$

2.9. Statistical analysis

Test scores were initially recorded as means and standard deviations (SD) in Microsoft Excel, and statistical data analysis was conducted in Python (version 3.11) using *pandas*, *numpy*, *scipy.stats*, *statsmodels*, *pingouin*, and *scikit-posthocs* libraries. The type I error was set at 5 % ($p < 0.05$). Firstly, the normality of the data distribution was assessed through the Shapiro-Wilk test. All the variables presented a normal-Gaussian distribution ($p > 0.05$). A three-way analysis of variance (ANOVA) involving the type of jump (CMJ versus HJ), phase (take-off versus landing), and leg dominance (dominant vs. non-dominant) with Bonferroni post hoc pairwise comparisons was conducted to determine significant main effects and interactions among the type of jump, phase, and leg dominance regarding the mean GA muscular activity of each unilateral and bilateral jump. Furthermore, Cohen's d was calculated as a measure of effect size (ES), interpreted according to conventional thresholds (0.2 = small, 0.5 = medium, 0.8 = large) (Cohen, 2013). Finally, Pearson's r correlations were conducted to examine the relationship between jump performance and inter-limb asymmetry, as well as between jump performance and EMG GA muscular activity during take-off and landing. Pearson's r correlation values were interpreted as negligible (0.00–0.10), weak (0.10–0.39), moderate (0.40–0.69), strong (0.70–0.89), and very strong (0.90–1.00), considering positive (+) or negative (−) associations between variables as well as 95 % confidence interval (CI) limits when statistical significance correlation was detected ($p < 0.05$) (Schober et al., 2018).

3. Results

3.1. Differences in gastrocnemius muscular activity considering the take-off and landing phases of bilateral and unilateral jumps

EMG activity was higher during the take-off compared to landing ($p < 0.05$), regardless of the type of jump (bilateral CMJ, bilateral HJ, unilateral CMJ, unilateral HJ) and the GA region (dominant lateral gastrocnemius (LG-DL), dominant medial gastrocnemius (MG-DL), non-dominant medial gastrocnemius (MG-NDL), non-dominant lateral gastrocnemius (LG-NDL)) (Figs. 2 and 3).

During the landing phase, higher EMG activity in the MG compared to the LG in both the dominant (LG-DL = 27.88 ± 11.04 % vs. MG-DL = 40.39 ± 15.38 %, p = 0.01, ES = 0.93) and non-dominant leg (LG-NDL = 30.00 ± 10.10 % vs. MG-NDL = 40.83 ± 18.28 %, p = 0.03, ES = 0.73) were found during bilateral (Fig. 2) and unilateral CMJ (LG-DL = 34.32 ± 10.97 % vs. MG-DL = 54.64 ± 15.38 %, $p < 0.01$, ES = 1.34; LG-NDL = 35.42 ± 14.00 % vs. MG-NDL = 46.22 ± 20.42 %, p = 0.04, ES = 0.62) (Fig. 3). This increased activation of the MG was also evident when comparing CMJ to HJ, showing greater values in bilateral and unilateral CMJ landings (Figs. 2 and 3).

3.2. Correlation between lower-limb asymmetry scores and jump performance

A moderate positive correlation was found between CMJ performance and bilateral take-off asymmetry (r = 0.43, p = 0.02, CI [0.05, 0.70]). Meanwhile, no significant correlations were found between the other inter-limb asymmetry indices and jump performance outcomes reported in Table 1 (Fig. 4).

3.3. Correlation between muscular activity at take-off and jump performance

In the CMJ condition, performance was negatively correlated with

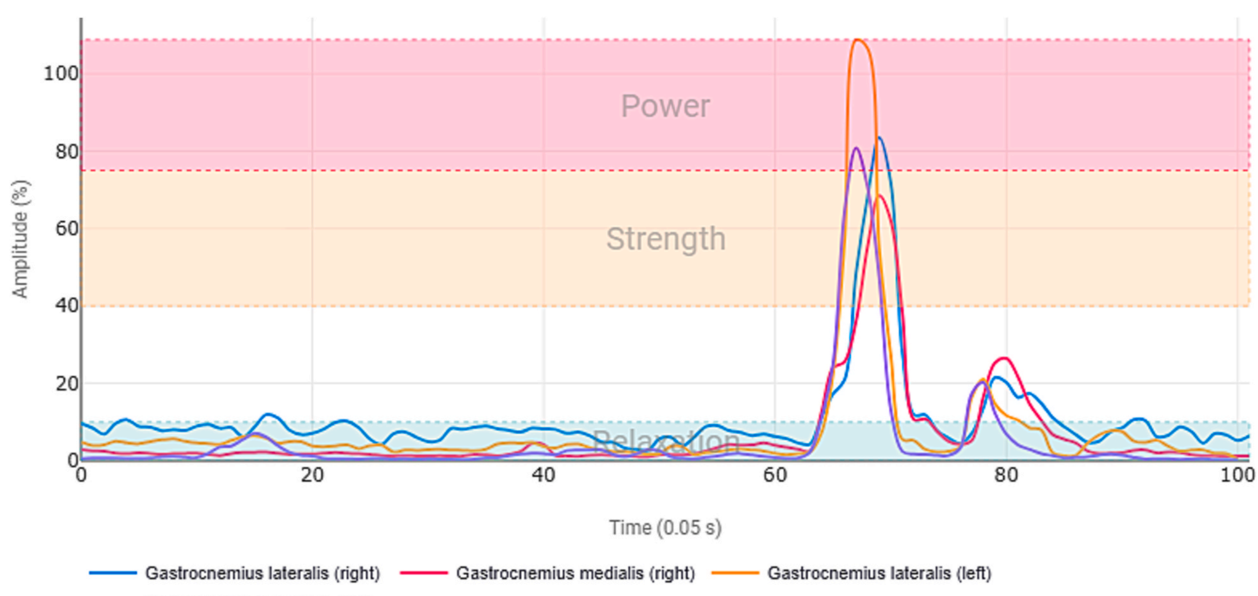

Fig. 1. Electromyographic signal of the lateral and medial gastrocnemius muscles of the dominant (right) and non-dominant (left) leg from a participant at impulse and landing phases during the bilateral horizontal jump. μV: Microvolts; s: Seconds.

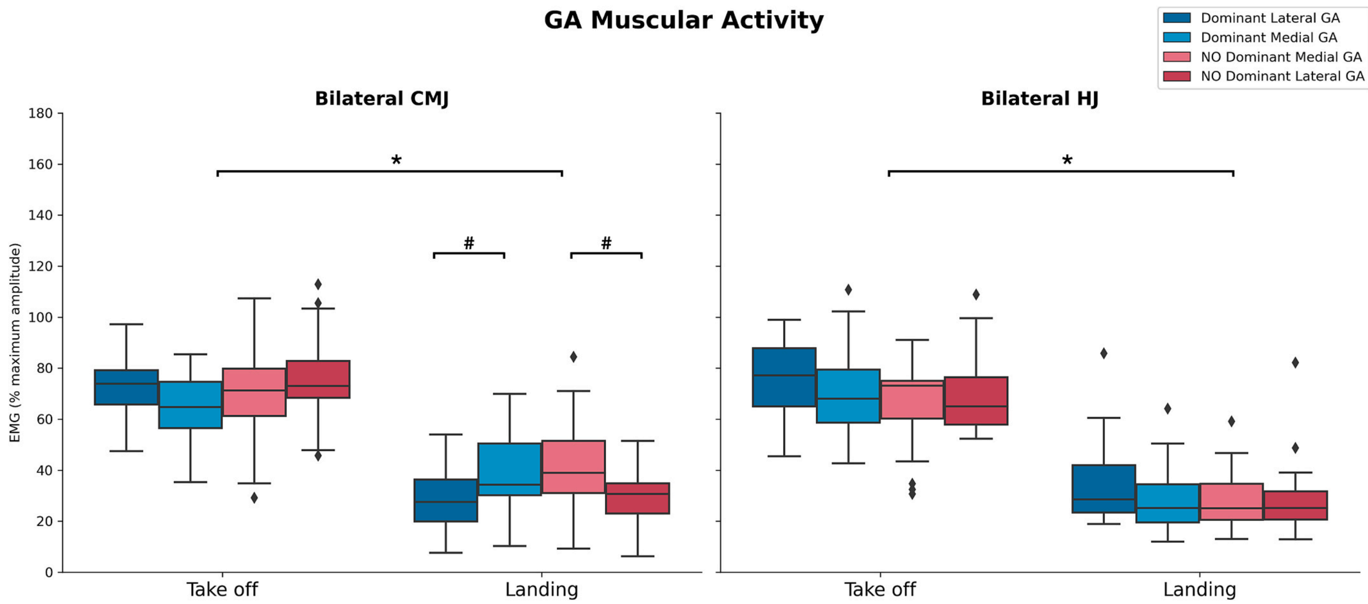

Fig. 2. Mean lateral (dark) and medial (light) gastrocnemius (GA) electromyography muscular activity of dominant leg (blue) and non-dominant leg (red) during the take-off and landing phases of the bilateral countermovement (CMJ) and horizontal jump (HJ), normalized by the maximum EMG amplitude during sprint (%). (*) $p < 0.05$ between phase and (#) $p < 0.05$ between GA regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

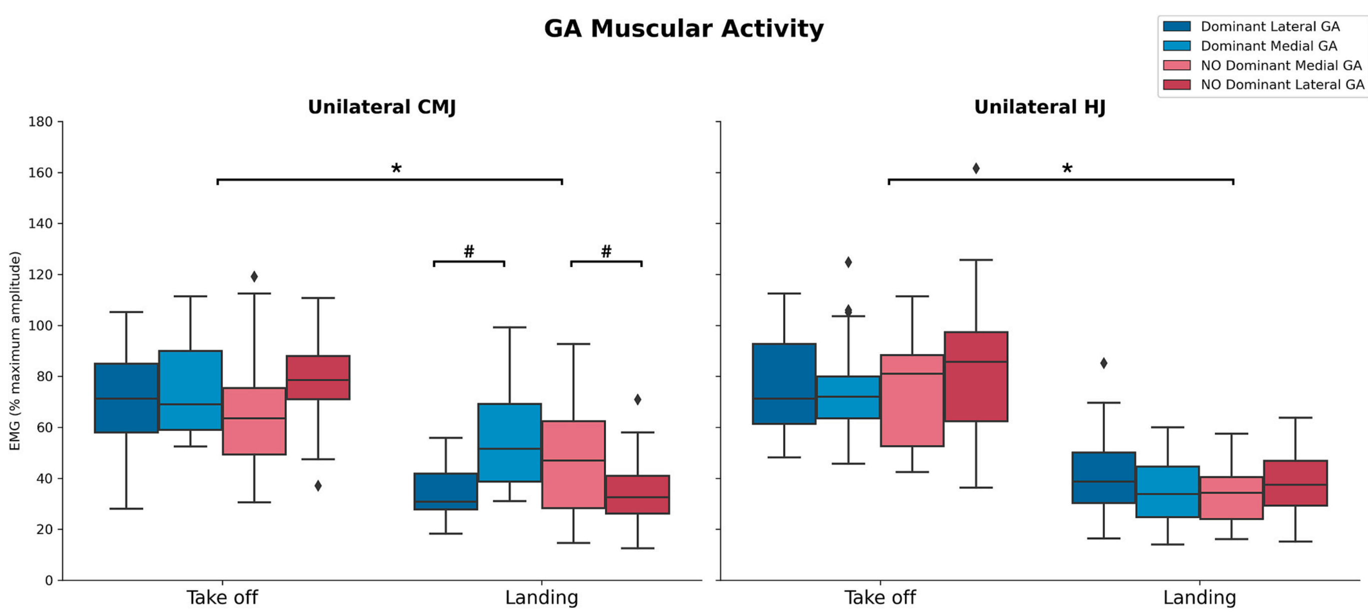

Fig. 3. Mean lateral (dark) and medial (light) gastrocnemius (GA) electromyography muscular activity of dominant leg (blue) and non-dominant leg (red) during the take-off and landing phases of the unilateral countermovement (CMJ) and horizontal jump (HJ), normalized by the maximum EMG amplitude during sprint (%). (*) $p < 0.05$ between phase and (#) $p < 0.05$ between GA regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the EMG activation of the non-dominant leg LG in both the CMJ (r = –0.40, p = 0.04, CI [-0.68, −0.01]) and the HJ unilateral condition (r = –0.45, p = 0.02, CI [-0.71, −0.07]) (Fig. 5). Similarly, HJ performance was negatively associated with EMG activity of the non-dominant leg MG during CMJ (r = –0.40, p = 0.04, CI [-0.68, −0.01]), as well as with the LG in the unilateral HJ (r = –0.44, p = 0.02, CI [-0.71, −0.06]) (Fig. 5). Additionally, unilateral non-dominant leg HJ performance was negatively correlated with the non-dominant leg LG activity recorded during CMJ (r = –0.39, p = 0.04, CI [-0.68, –0.00]) (Fig. 5).

3.4. Correlation between muscular activity at landing and jump performance

A negative moderate correlation was found between HJ performance and EMG activity from the non-dominant leg MG during unilateral HJ landing (r = -0.48, p = 0.01, CI [-0.73, −0.12]) (Fig. 6). Similarly, CMJ and unilateral dominant leg CMJ performance were negatively associated with EMG activity from the non-dominant leg MG during unilateral HJ landing, with correlation coefficients of r = -0.43 (p = 0.03, CI [-0.70, −0.05]) and r = -0.41 (p = 0.04, CI [-0.69, −0.03]), respectively (Fig. 6). Additionally, a significant negative association was observed

Table 1
Descriptive Statistics of Jump Performance.

	Jump Condition	Mean ± Standard Deviation
CMJ Jump Height (cm)	Bilateral	33.79 ± 9.71
	Unilateral Dominant	15.42 ± 4.88
	Unilateral Non-Dominant	14.30 ± 5.09
HJ Jump Length (m)	Bilateral	3.01 ± 0.64
	Unilateral Dominant	2.78 ± 0.61
	Unilateral Non-Dominant	2.74 ± 0.63

Data are presented as mean ± standard deviation for the 26 physically active participants included in the study; CMJ: Countermovement Jump; HJ: Horizontal Jump.

between HJ performance and MG activation during unilateral CMJ (r = -0.43, p = 0.03, CI [-0.70, −0.05]) (Fig. 6).

4. Discussion

The primary aim of this study was to analyse the inter-limb neuromuscular activity of the GA muscle during the take-off and landing phases of bilateral and unilateral explosive jumps. The main findings demonstrated a consistently greater EMG activation during the take-off phase compared to landing, independent of the type of jump (i.e., CMJ and HJ) or the limb dominance (i.e., unilateral dominant CMJ, unilateral non-dominant CMJ, unilateral dominant HJ, and unilateral non-dominant HJ). In the landing phase, the CMJ showed higher MG

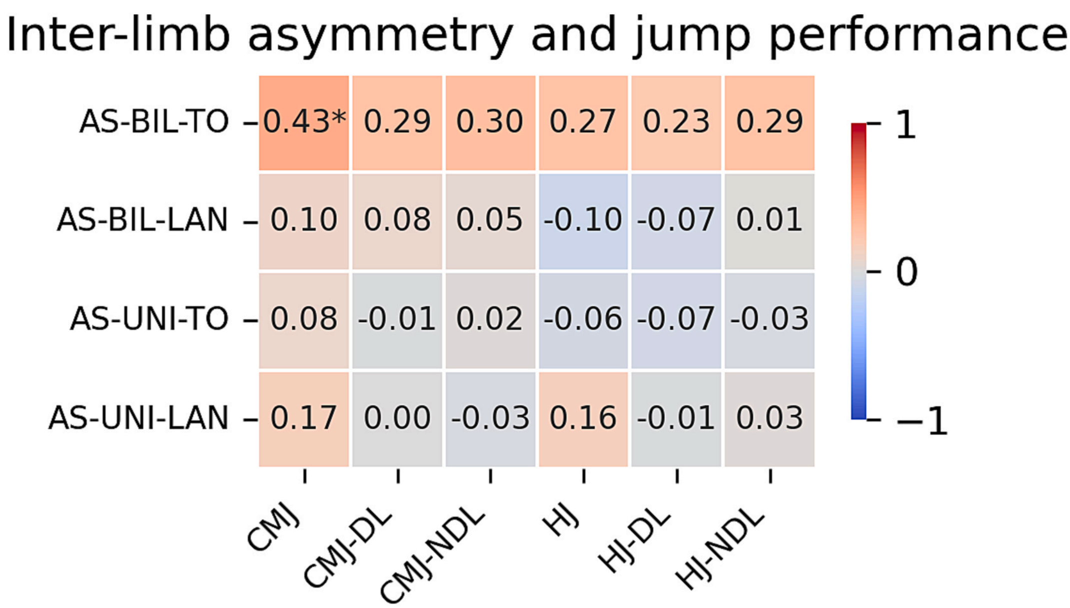

Fig. 4. Correlation between jump performance and inter-limb asymmetry. AS-BIL-TO: Bilateral asymmetries during take-off; AS-BIL-LAN: Bilateral asymmetries during landing; AS-UNI-TO: Unilateral asymmetries during take-off; AS-UNI-LAN: Unilateral asymmetries during landing; CMJ: Counter movement jump; HJ: Horizontal jump; DL: Dominant leg; NDL: Non-dominant leg. Colour intensity represents the strength and direction of the correlation (red: positive; blue: negative), while (*) represents p < 0.05. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

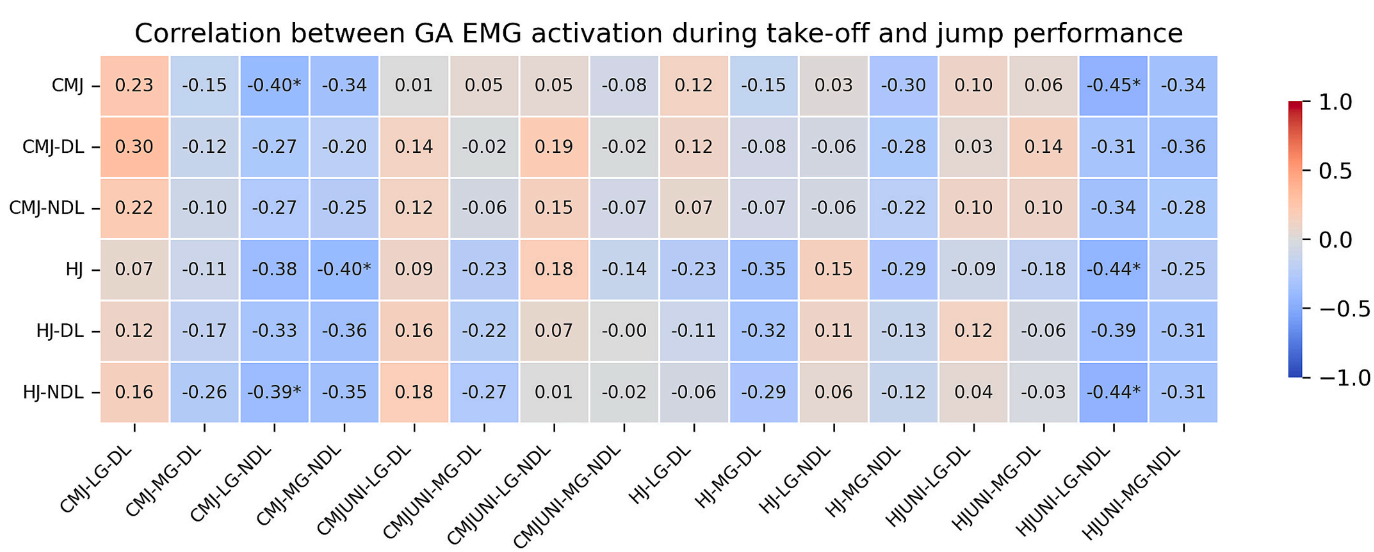

Fig. 5. Correlation between performance and EMG take-off values. CMJ: Counter movement jump; HJ: Horizontal jump; DL: Dominant leg; NDL: Non-dominant leg; CMIUNI: Unilateral counter movement jump; HJUNI: Unilateral horizontal jump; LG: Lateral gastrocnemius; MG: Medial gastrocnemius. Colour intensity represents the strength and direction of the correlation (red: positive; blue: negative), while (*) represents p < 0.05. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

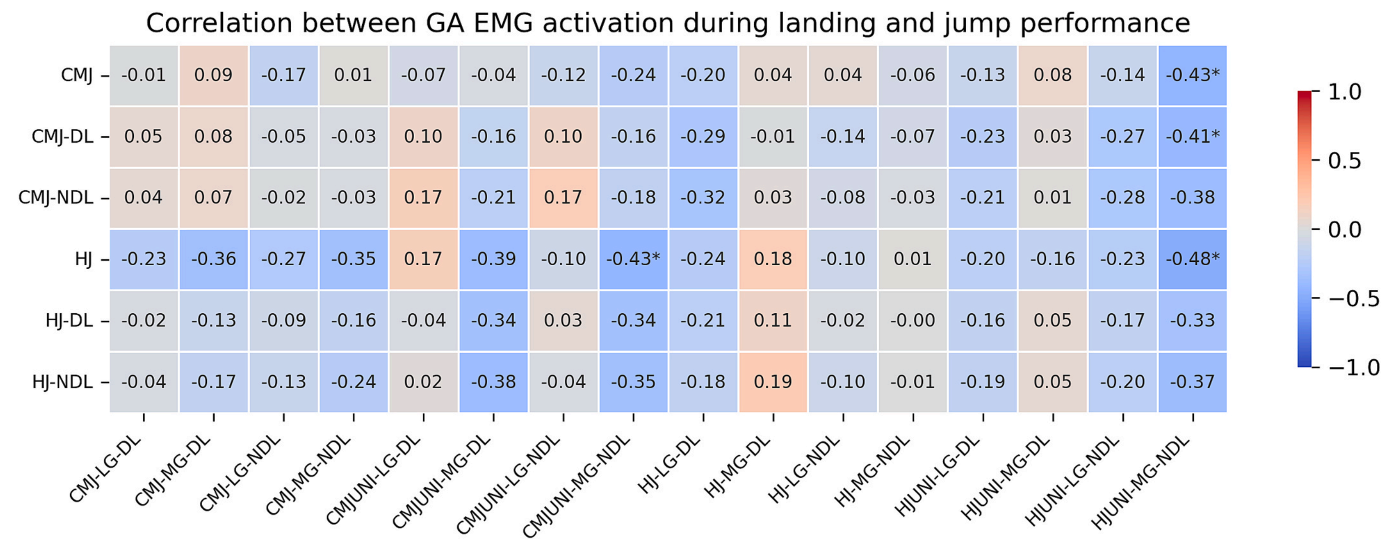

Fig. 6. Correlation between performance and EMG landing values. CMJ: Counter movement jump; HJ: Horizontal jump; DL: Dominant leg; NDL: Non-dominant leg; CMIUNI: Unilateral counter movement jump; HJUNI: Unilateral horizontal jump; LG: Lateral gastrocnemius; MG: Medial gastrocnemius. Colour intensity represents the strength and direction of the correlation (red: positive; blue: negative), while (*) represents $p < 0.05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

activation compared to LG in bilateral and unilateral dominant and non-dominant legs. Furthermore, a moderate positive correlation was observed between bilateral take-off asymmetry and CMJ performance, while several negative correlations were found between non-dominant limb EMG activity and performance outcomes. Based on the results obtained, the first hypothesis was accepted, while the second hypothesis was partially accepted.

4.1. Gastrocnemius activation in CMJ and HJ unilateral and bilateral jumps

The current findings revealed a consistent increase in EMG activity during the take-off phase compared to landing across all jump modalities (bilateral and unilateral CMJ and HJ), and this pattern was evident in both GA bellis and both limbs. This result highlights the increased neuromuscular demand associated with the propulsive phase (take-off), regardless of the task requirements (type of jump), and is in line with research that proved increased activation in explosive movements (Ferri-Caruana et al., 2024; Werkhausen et al., 2021).

Concerning the landing phase, the CMJ showed a specific increase in activation of the MG over the LG in both bilateral and unilateral actions. This predominant activation reflects the MG's dominant role in impact absorption and joint stabilization during the eccentric deceleration of landing (Hamard et al., 2021). Previous work has reported that MG and LG do not share identical functional or mechanical profiles (Ahn et al., 2011; Hamard et al., 2021) and that MG responds more effectively during ankle plantar flexion, while LG may function as an energy transfer mediator between the knee and ankle joints (Fiebert et al., 1998; Héroux et al., 2014). Evidence from motor unit discharge analyses suggests that MG and LG are not tightly coupled by a shared neural drive, enabling functionally independent recruitment patterns depending on task (Hug et al., 2021). This neuromechanical decoupling may allow the specific stabilizing roles of the MG during dynamic deceleration, particularly in high-impact vertical tasks such as CMJ landings (Hamard et al., 2021). These distinctions support our results, reinforcing the differentiated neuromechanical roles for each head of the gastrocnemius.

Furthermore, the specificity of muscle activation patterns observed between CMJ and HJ landings appears tightly linked to the mechanical requirements and directionality of each jump. In CMJ, vertical displacement imposes an eccentric braking phase immediately after ground contact, necessitating rapid absorption of downward kinetic energy (Hamard et al., 2021). In contrast, the HJ involves a primarily horizontal displacement and force vector, resulting in a more gradual deceleration phase and lower vertical impact forces (Benjanuvatra et al., 2013). This distinction translated into a more equilibrated activation between MG and LG during HJ landings, suggesting a synergistic contribution of both muscle bellies to horizontal braking. Such task-specific neuromuscular strategies underscore how the mechanical context (i.e., direction of movement and ground reaction forces) influences the GA activation profile, further supporting the notion that MG and LG fulfil distinct yet complementary roles in response to movement demands (Ferri-Caruana et al., 2024; Hug et al., 2021).

Interestingly, no significant differences in GA activation patterns were observed between unilateral and bilateral executions within the same type of jump (i.e., CMJ and HJ), suggesting a robust motor strategy that remains relatively invariant to limb configuration under the same biomechanical contexts. These findings support the concept of "task-specific consistency" in neuromuscular control, suggesting that within a given jump modality, the central nervous system enhances reproducible motor patterns to ensure reliability and efficiency across different support conditions (Bishop et al., 2018). Although unilateral tasks are generally assumed to increase neuromuscular demand due to a reduced base of support and higher stabilization requirements (Benjanuvatra et al., 2013; Bishop et al., 2017), our results suggest that these effects may not significantly influence GA activation in controlled, explosive tasks, such as the CMJ and HJ, probably due to the participants' training level and their familiarity with the jumps tasks.

4.2. Correlation between asymmetries and performance

The moderate positive correlation between CMJ performance and bilateral take-off asymmetry suggests that greater inter-limb discrepancies in force production do not necessarily affect vertical jump height. In fact, they may coexist with or even support better performance outcomes in certain athletes. This result challenges the traditional view that symmetry is always indicative of superior function or efficiency (Bell et al., 2014; Bishop et al., 2018). But aliens with studies that have shown that asymmetries in neuromuscular or kinetic variables do not uniformly translate into performance decrements and may instead reflect individualized compensatory strategies or dominant-limb reliance during bilateral actions (Bishop et al., 2018; Bell et al., 2014). Specifically, Bishop et al. (2018) reported that moderate inter-limb asymmetries in trained athletes did not negatively affect sprint, jump, or change-of-direction performance, highlighting a context-dependent influence of asymmetry on motor output.

Moreover, the lack of significant associations between asymmetry indices and performance in the HJ condition further underscores the task-specificity of the relationship. HJ likely allows for a more distributed coordination of force across lower-limb segments, making them less sensitive to localized muscle activation asymmetries. The directional nature of the HJ, which emphasizes horizontal propulsion and multi-joint integration, may reduce the impact of inter-limb differences observed at take-off (Benjanuvatra et al., 2013). This is in contrast with the CMJ, where vertical propulsion depends more directly on synchronized bilateral ankle-knee-hip extension, potentially amplifying the performance effects of asymmetry at the plantar flexor level (Benjanuvatra et al., 2013; Bishop et al., 2018). In this context, asymmetry in CMJ may reflect a form of functional laterality or preferential force contribution from the dominant limb, a phenomenon previously described as bilateral facilitation or lateralization in explosive tasks (Ebben et al., 2009). These findings suggest that, while asymmetries are often viewed as detrimental, they may also represent stable motor patterns adapted to the task demands, athlete experience, or individual biomechanics, particularly in bilateral vertical movements (Bishop et al., 2018).

4.3. Correlation between gastrocnemius activation and performance

The negative associations observed between jump performance and EMG activity of the non-dominant GA (both LG and MG) across multiple conditions point toward a potential maladaptive neuromuscular strategy. Higher activation levels in the non-dominant LG and MG during both take-off and landing phases were consistently linked to reduced jump outcomes in CMJ and HJ, suggesting that excessive muscular output in these regions may not reflect effective force production, but rather a compensatory response to neuromechanical inefficiencies. This interpretation aligns with prior findings that excessive or poorly timed muscle activation can reduce movement efficiency by disrupting the coordination between muscle groups or overloading specific segments of the kinetic chain (Bishop et al., 2018; Bell et al., 2014). Notably, Bishop et al. (2017) emphasized that asymmetries may only become performance-detrimental when they exceed an athlete's ability to compensate or when they occur in motor tasks that require high inter-limb coordination.

Moreover, the inverse relationship between non-dominant leg MG activation during landing and performance (particularly in the HJ condition) may reflect suboptimal eccentric load management. As previously proposed by Hamard et al. (2021), excessive MG activation without appropriate fascicle behavior (e.g., controlled isometric action) can interfere with the efficiency of the muscle–tendon unit, reducing elastic recoil and energy transfer during the braking phase. Given that HJ places high demands on horizontal deceleration and reacceleration, disproportionate MG activity in the non-dominant limb could compromise the coordinated transfer of momentum, limiting propulsion effectiveness. Additionally, prior research has suggested that lower-limb asymmetries (especially in less trained athletes) are often accompanied by altered motor control and force directionality, potentially increasing metabolic cost or delaying optimal ground contact timing (Benjanuvatra et al., 2013; Ebben et al., 2009). These maladaptive patterns may manifest as elevated EMG output in weaker or less efficient limbs, particularly under high-demand, unilateral, or directionally complex tasks, such as HJ.

4.4. Limitations

This study acknowledges some limitations. Firstly, although the medial and lateral GA bellies were the focus due to their relevance in explosive plantar flexion, other muscles, such as the soleus and tibialis anterior, which contribute to ankle joint stability, could have been assessed. Secondly, the EMG signal was not analyzed in the time continuum, which limited the ability to precisely assess the timing, onset, and duration of GA activation during the distinct subphases of the jump. Thirdly, weight bearing was not measured or controlled prior to bilateral vertical jumps to explicitly exclude trials where participants might have stood asymmetrically. While efforts were made to standardize the starting position, unquantified initial load asymmetries could have influenced jump initiation and subsequent neuromuscular activation patterns.

4.4.1. Practical applications

The present findings offer several practical implications for sports performance professionals aiming to enhance jump outcomes and monitor neuromuscular efficiency. The identification of negative associations between elevated EMG output in the non-dominant limb and performance suggests that screening for excessive activation may help detect compensatory or inefficient motor strategies.. Importantly, the lack of significant performance impairment associated with moderate take-off asymmetries suggests that such asymmetries are not inherently detrimental and may reflect adaptive dominance patterns. Coaches should therefore avoid over-correcting asymmetries in the absence of performance or injury concerns, instead focusing on functional efficiency and task-specific motor control. Finally, given the task-specific differences between vertical and HJ, training programs should be movement-specific, with particular attention to vector orientation, limb contribution, and phase-specific muscle demands.

4.5. Future research

Future investigations should aim to expand on the current findings by incorporating a time-resolved analysis of muscle activation patterns throughout the entire jump cycle. The use of continuous EMG recording synchronized with kinematic and kinetic data would enable a more precise understanding of the temporal coordination and phasic roles of the GA and related musculature during take-off and landing. Additionally, extending EMG analysis beyond the GA would offer a more comprehensive perspective on lower-limb neuromuscular strategies involved in jump performance and impact control.

It would also be valuable to explore how sex, age, and training experience modulate neuromuscular patterns, given the growing body of evidence suggesting population-specific adaptations (Bell et al., 2014; Bishop et al., 2017). Finally, the integration of individualized movement profiling with machine learning techniques may offer novel insights into how unique neuromechanical signatures contribute to performance and adaptation. This personalized approach could help tailor training and rehabilitation interventions based on each athlete's motor strategies, asymmetry profiles, and response patterns under different jump conditions.

5. Conclusion

This study provides novel insights into the neuromuscular activation patterns of the GA muscle during bilateral and unilateral CMJ and HJ tasks, highlighting phase- and region-specific differences, particularly concerning limb dominance and jump modality. The results highlight the relationship between muscle activation, asymmetry, and performance, indicating that higher activation (especially in the non-dominant limb) may reflect compensatory or inefficient motor strategies rather than enhanced output. Furthermore, our findings support the notion that while functional asymmetry and limb dominance are inherent in human movement, elevated activation in non-dominant GA muscles may serve as a marker for inefficient motor strategies. This is especially relevant in tasks involving explosive propulsion and controlled landings, where optimal performance depends not only on peak force but also on timing, coordination, and muscle–tendon efficiency. Practitioners should therefore consider both the magnitude and distribution of neuromuscular output when evaluating jump performance and identifying potential compensatory mechanisms.

6. Patient consent

All participants were free from injury during testing and voluntarily participated in the study. Athletes signed an informed consent form giving their assent to participate.

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CRediT authorship contribution statement

Ana Ferri-Caruana: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joaquín Martín Marzano-Felisatti:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Carlos Sendra-Pérez:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jose Ignacio Priego-Quesada:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Ethics approval

The experimental procedures were approved by the Ethics Committee of the University of Valencia (1973315) and were conducted following the latest revision of the Declaration of Helsinki.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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