applied sciences

MDPI

Article

Direction-Dependent Limb Asymmetries in Female Lateral Jumps: A Ground Reaction Force and Knee Torque Study

Michalina Błażkiewicz [1,*], Aleksandra Malec [2], Marta Trawczyńska [2], Michał Skalik [3] and Jacek Wąsik [3,*]

[1] Faculty of Rehabilitation, The Józef Piłsudski University of Physical Education in Warsaw, 00-968 Warsaw, Poland
[2] Student Biomechanics Club, Faculty of Rehabilitation, The Józef Piłsudski University of Physical Education in Warsaw, 00-968 Warsaw, Poland; am78394@stud.awf.edu.pl (A.M.); mt78457@stud.awf.edu.pl (M.T.)
[3] Institute of Physical Culture Sciences, Jan Długosz University in Częstochowa, 42-217 Częstochowa, Poland; michal.skalik@ujd.edu.pl
* Correspondence: michalina.blazkiewicz@awf.edu.pl (M.B.); j.wasik@ujd.edu.pl (J.W.)

Abstract

Background: Movement symmetry in the lower limbs is critical for biomechanical efficiency, injury prevention, and athletic performance. Lateral (sideways) jumping challenges force production and control in the frontal plane and provide a unique assessment of neuromuscular coordination that may not be detected through sagittal-plane tasks such as running or vertical jumping. This study aimed to evaluate limb asymmetries in isometric knee muscle torque and ground reaction forces (GRFs) during lateral jumps in healthy young women, using the Symmetry Index (SI) to quantify differences between limbs. Methods: Twenty right-limb dominant females (mean age: 20.65 ± 4.51 years) participated in the study. Isometric torque of the knee flexors and extensors was measured using a dynamometric testing station. Lateral jumps were performed onto dual force platforms, with GRF components (vertical (PD), anterior–posterior (AP), mediolateral (ML)) recorded separately for rightward and leftward jumps. SI was calculated for all parameters to determine side-to-side asymmetries, and paired Student's *t*-tests were used for statistical comparisons. Results: Right-limb dominance was evident in both knee flexor and extensor torque. Significant asymmetries were observed across all GRF components, varying with jump direction. The trailing limb in each jump direction typically generated greater propulsion forces. In lateral jumps, the trailing limb is generally the leg positioned opposite to the direction of travel, playing a primary role in generating propulsion and absorbing forces during take-off. SI values revealed both inter-individual variability and consistent direction-dependent asymmetry patterns. Conclusions: The or-posterior and vertical components, with greater loading on the dominant leg. Muscle torque measurements also revealed imbalances, with flexors showing more symmetry than extensors. These findings underline the importance of assessing load symmetry to prevent injury and guide rehabilitation.

Keywords: jumps; kinetics; ground reaction forces

check for updates

Academic Editor: Mark King

Received: 16 July 2025
Revised: 14 August 2025
Accepted: 18 August 2025
Published: 20 August 2025

Citation: Błażkiewicz, M.; Malec, A.; Trawczyńska, M.; Skalik, M.; Wąsik, J. Direction-Dependent Limb Asymmetries in Female Lateral Jumps: A Ground Reaction Force and Knee Torque Study. *Appl. Sci.* **2025**, *15*, 9150. https://doi.org/10.3390/app15169150

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Lateral movements, including side jumps, are essential in numerous sports disciplines that require rapid changes of direction, lower limb stabilization, and trunk control. These movements are especially critical in sports, such as basketball, handball, soccer, and combat sports.

Consequently, they have been widely used in motor performance assessment, functional training design, and rehabilitation protocols [1,2]. The present study investigates the symmetry of the extreme values of ground reaction force (GRF) components during lateral jumps in women with a dominant right lower limb, together with the symmetry of maximum knee flexion and extension torques during isometric measurements, presenting this objective early to frame the study's rationale.

During lateral jumps, considerable ground reaction forces (GRFs) are generated, and these have been identified as key indicators of frontal plane force production and braking efficiency [3,4]. Through such force analysis, dynamic neuromuscular control and explosive power output can be evaluated, both of which are essential for performance and injury prevention.

An increasing number of studies have been conducted on the biomechanics of jumps and explosive movements due to their diagnostic relevance in assessing athletic capacity [5–7]. For example, it has been shown that vertical jump performance is significantly correlated with sprint speed in elite athletes, indicating shared neuromechanical mechanisms [8]. Furthermore, neuromotor reactivity is modifiable through specialized training interventions, such as stroboscopic training, which improved reaction time in volleyball players [9]. Muscle activity variability has also been investigated across various movement tasks. For instance, the firing frequency of primary movers during the bench press was found to vary depending on the movement phase, particularly around the "sticking point" [10].

One critical aspect of movement biomechanics is the symmetry of load distribution between the lower limbs. Asymmetries in muscle strength and torque have been associated with overload, increased injury risk, and reduced functional capacity [11,12]. Even among healthy, physically active individuals, significant differences have been observed between dominant and non-dominant limbs, especially during dynamic tasks [13–15]. In both vertical and lateral jumps, such asymmetries have been reported not only in vertical force components but also in anterior–posterior (AP) and medial–lateral (ML) directions, requiring specialized tools like force platforms for accurate detection [16].

The Symmetry Index (SI) is often used to quantify these differences objectively [17]. Studies have shown that force and strength asymmetries can reach several tens of percent and are frequently not perceived subjectively [18]. While research on vertical and horizontal jumping is extensive, fewer studies have focused on lateral jumps, particularly ground reaction force (GRF) symmetry in female athletes, despite its importance for athletes, physiotherapists, and strength and conditioning coaches [19,20].

From a biomechanical perspective, symmetry in lateral jumping is analyzed by comparing kinetic and kinematic parameters between limbs across different phases: pre-load, take-off, flight, and landing. These parameters include joint angles, GRFs, moment arms, muscle activation patterns, and time-to-peak force. Deviations from symmetry have been interpreted as indicators of functional deficits, muscular imbalances, or compensatory strategies, often associated with overuse injuries or previous trauma. In athletic populations, the presence of asymmetries during lateral jumping has been linked to reduced performance potential and an elevated risk of injury, particularly in sports requiring rapid directional changes. In rehabilitation contexts, especially after anterior cruciate ligament (ACL) reconstruction, lateral jump tasks have been used in later stages of recovery to evaluate readiness to return to sport [21,22].

By integrating both GRF analysis and isometric torque assessment (Figure 1), this study seeks to explore the relationship between muscle strength and the distribution of dynamic loads during lateral jumps. These findings aim to provide insights into frontal

plane biomechanics with practical implications for athletic training, injury prevention, and rehabilitation strategies.

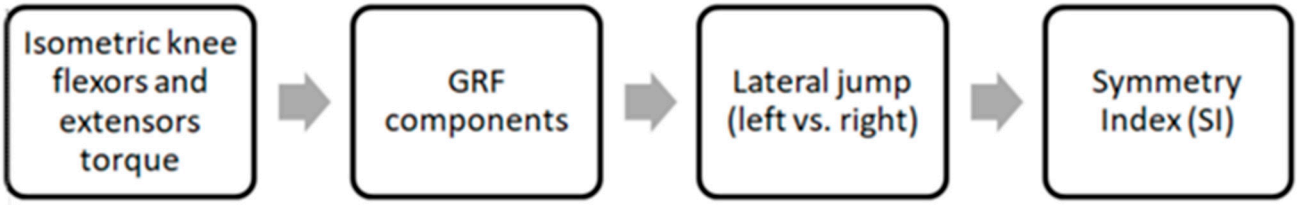


Figure 1. Conceptual diagram of the relationship between knee torque, ground reaction force (GRF) components, and movement direction.

2. Materials and Methods

2.1. Characteristics of Study Participants and Procedures

The study involved 20 female participants with a mean age of 20.65 ± 4.51 years, mean height of 167.75 ± 5.50 cm, and mean body mass of 60.55 ± 6.08 kg. Inclusion criteria required participants to have no history of muscular or neurological disorders, no lower limb injuries within the past six months, and right lower limb dominance, defined as the preferred leg used for kicking a ball [23]. Exclusion criteria included any balance impairments, current use of medications affecting the nervous system, or left lower limb dominance.

The study received ethical approval from the University's Institutional Review Board (ref. no. SKE01-15/2023) and was carried out in accordance with the principles outlined in the Declaration of Helsinki. Prior to participation, all individuals were thoroughly informed about the study's purpose and procedures.

Two types of measurements were conducted. Using the TBK3 testing station, isometric measurements of knee flexor and extensor muscle torque were assessed (Figure 2A,B). Each participant performed the test three times, with each trial lasting 3 seconds. The highest value from the three trials was used for analysis.

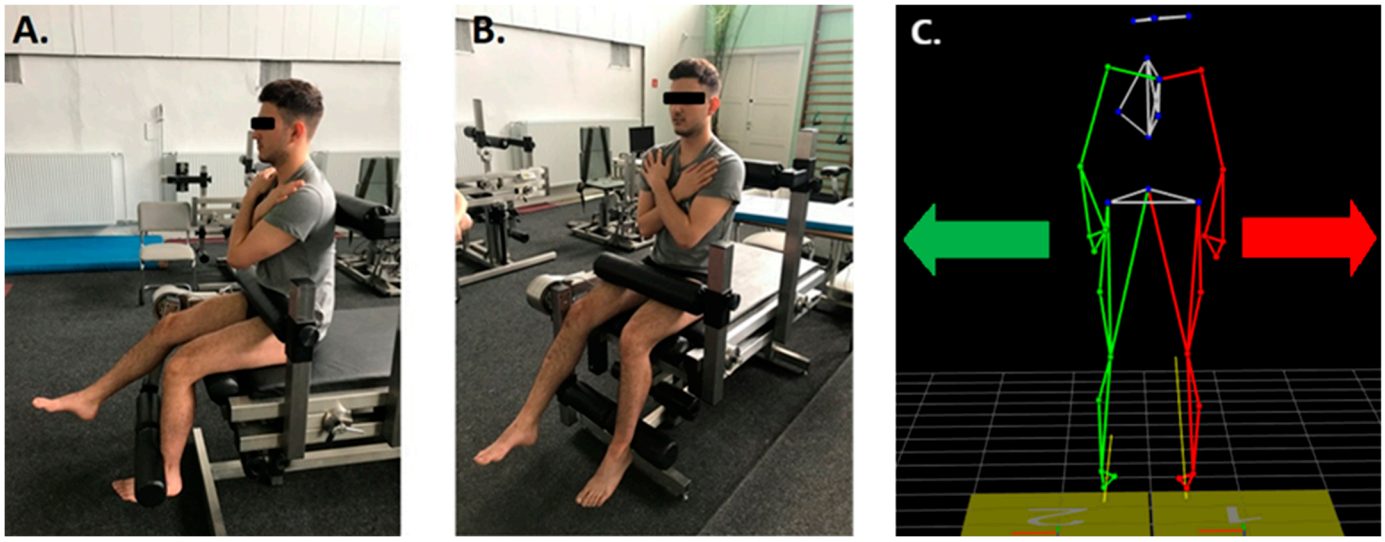


Figure 2. Two measurements: (**A**,**B**) position for assessing the torque of the knee flexor and extensor muscles; (**C**) starting position for a lateral jump, where green indicates the left side and red indicates the right side.

The second measurement was performed using two Kistler piezoelectric force platforms (1000 Hz, Kistler Holding AG, Winterthur, Switzerland) permanently installed side by side on the floor. Participants stood with one foot on each platform, with feet hip-width

apart. The order of lateral jump trials (left vs. right) was fixed rather than randomized. Participants first jumped to the left and then to the right. Each jump was performed only once to avoid both learning effects and fatigue effects. When ready, they performed a lateral jump, first to the right side, and then to the left in the next trial (Figure 2C). The task was to jump as far as possible. However, the jump distance was not recorded, as participants often made an additional step after landing to maintain balance. The extreme values of the three components of the ground reaction forces (GRFs) were taken for analysis. Values are expressed as the relative to body weight (N/kg) to improve inter-subject comparability and reduce variability due to anthropometric differences.

2.2. Parameters and Statistical Analysis

Statistical analysis was performed using Statistica v. 12 (StatSoft, Tulsa, OK, USA), with the level of significance set at $p < 0.05$. The Shapiro–Wilk test was used to assess the normality of all parameters. Since all maximal and minimal values of each ground reaction force (GRF) component and knee muscle torques followed a normal distribution, a paired Student's *t*-test was applied to compare these values within each GRF component, separately for leftward and rightward jumps. Additionally, for each of the parameters mentioned above, the effect size (Cohen's d) [24] was calculated using following formula: $D = \frac{t}{\sqrt{n}}$, where t is the value from the *t*-test, and n is the number of paired observations. Effect sizes were interpreted as small (d $\approx$ 0.20), medium (d $\approx$ 0.50), and large (d $\approx$ 0.80) [24].

Subsequently, the Symmetry Index (SI) was calculated for the knee flexors and extensors muscle torque, as well as for the maximal and minimal values of ground reaction force (GRF), separately for leftward and rightward jumps, using the following formula: [25] $SI = \frac{(L-R)}{0.5\times(R+L)} \times 100\%$, where L and R denote the left (non-dominant) and right lower (dominant) limb, respectively. While the original formula includes an absolute value in the numerator, in this case, the absolute value was omitted to retain information about which side determined the sign of the SI. Retaining the sign in the Symmetry Index (SI) enables detection of systematic asymmetries, indicating whether greater force production originates from the dominant or non-dominant limb. This directionality is valuable in performance and rehabilitation analysis because it reveals limb-specific functional roles, compensatory strategies, and deficits that would be hidden if only magnitude were considered. Evidence suggests that evaluating both magnitude and direction provides a clearer understanding of performance variability, helping to distinguish persistent, clinically relevant imbalances from normal fluctuations linked to training adaptations or natural motor variability [26]. As the direction of asymmetry can vary substantially between tasks, capturing it improves the ability to individualize interpretation and monitor recovery. In this study, it was assumed that the non-dominant limb, acting as the supporting limb, should produce higher muscle force to yield a positive SI value [27]. The same approach was applied to the peak ground reaction force values for each component.

To explore the functional relationship between knee muscle strength and force production asymmetries, Pearson correlation analyses were performed between knee torque (extension and flexion) and GRF symmetry indices for maximal and minimal values in the medial–lateral (ML), anterior–posterior (AP), and vertical (PD) directions. These analyses allowed for the evaluation of whether inter-limb differences in muscle torque were systematically associated with asymmetries in ground reaction forces during lateral jumps.

3. Results

3.1. Muscle Torque at the Knee Joint

The muscle torque values for both the knee flexors and extensors followed a normal distribution; therefore, a Student's *t*-test was used for comparison. The analysis showed that the muscle torque of both the knee extensors and flexors of the right lower limb was significantly ($p < 0.001$) higher than that of the left (Figure 3). Specifically, the torque of the right extensors (165.8 ± 30.27 Nm) was 11.9% higher than that of the left extensors (148.15 ± 30.20 Nm), and the torque of the right flexors (86.75 ± 25.03 Nm) was 10.4% higher compared to the left flexors (78.55 ± 19.96 Nm).

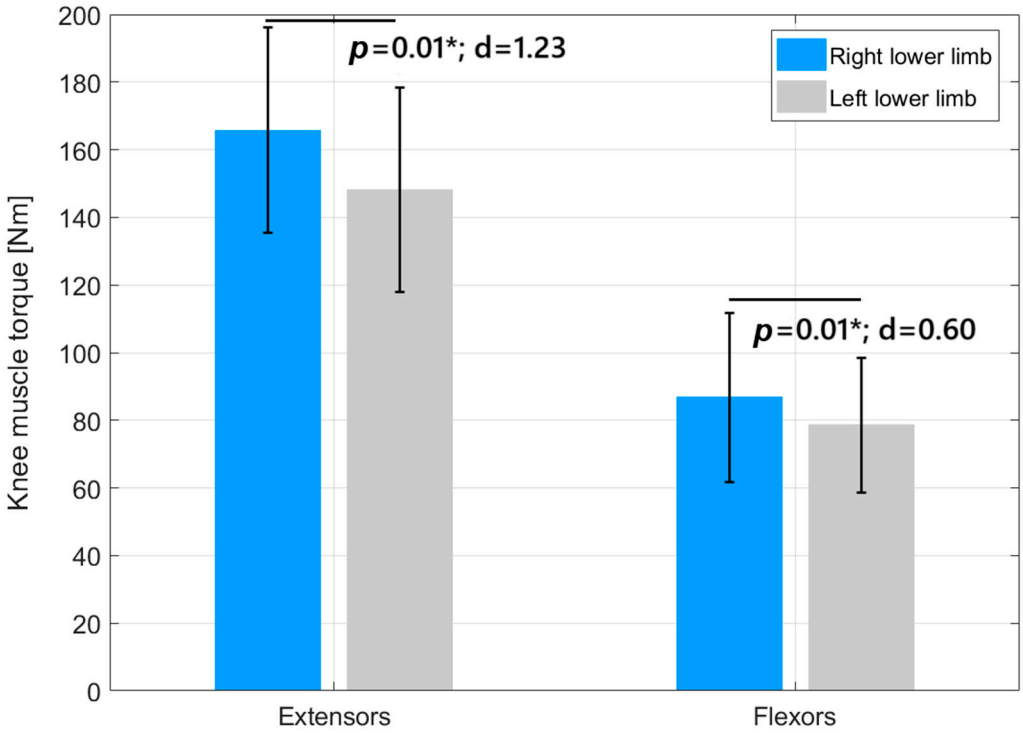


Figure 3. Mean and standard deviation of knee extensors and flexors muscle torque. Statistically significant differences are indicated with an asterisk (*) and reported with the corresponding $p-$values and Cohen's d effect sizes.

The SI values for the knee extensors were positive in two participants, at 4.56% and 1.44%, indicating slight asymmetry. In contrast, the remaining 18 participants showed negative values, with asymmetry ranging from −2.13% to −29.85%. A similar trend was observed for the knee flexors. Two participants had positive SI values, one displaying a considerable asymmetry of 68.9%, and the other a minor asymmetry of 2.66%. The remaining 18 participants again showed negative values, with the asymmetry ranging from −1.25% to −28.57%.

3.2. Vertical Component of the Ground Reaction Force

During the leftward jump, the maximum vertical component of the ground reaction force (GRF) was, significantly, 23.52% higher in the right/dominant limb compared to the left/non-dominant limb (12.97 ± 2.05 vs. 10.50 ± 0.91 N/kg, $p = 0.001$) (Figure 4A), indicating stronger vertical force generation. Conversely, the minimal vertical GRF was, significantly, 83.33% lower for the left/non-dominant limb (−0.22 ± 0.16 vs. −0.12 ± 0.09 N/kg, $p = 0.01$) (Figure 4B), reflecting greater force absorption.

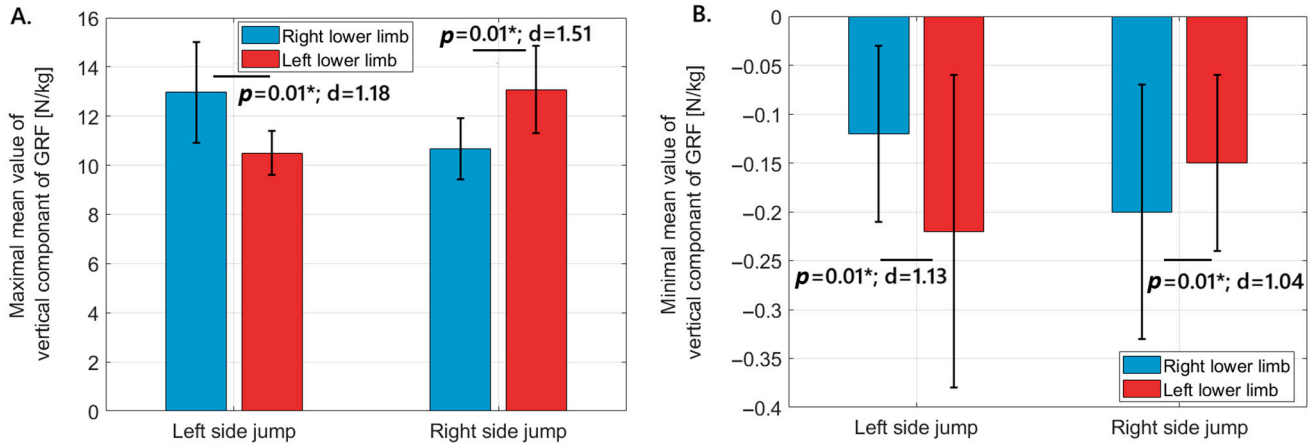


Figure 4. Mean and standard deviation of (**A**) maximal and (**B**) minimal values of the vertical ground reaction force (GRF) component during side jumps, shown separately for leftward and rightward jump directions. Values are shown for the dominant (right lower limb) and non-dominant (left lower limb). Statistically significant differences are indicated with an asterisk (*) and reported with the corresponding $p-$values and Cohen's d effect sizes.

In the rightward jump, the pattern was reversed. The left/non-dominant limb exhibited a significantly higher maximum vertical GRF compared to the right/dominant limb (13.08 ± 1.78 vs. 10.68 ± 1.24 N/kg, $p = 0.02$) (Figure 4A). The minimal vertical GRF was significantly lower for the right/dominant limb (-0.20 ± 0.13 vs. -0.15 ± 0.09 N/kg, $p = 0.001$) (Figure 4B), indicating greater force absorption on the right side.

Symmetry Index (SI) analysis further highlighted direction-dependent asymmetries (Table 1). For the leftward jump, only two participants had positive SI values for the maximum vertical GRF (7.77% and 1.49%), whereas the remaining 19 participants exhibited negative SI values (-0.47% to -59.41%), indicating higher force production in the right limb. For minimal vertical GRF, 19 participants showed positive SI values (23.08% to 102.41%), indicating greater force absorption in the left limb; only one participant was near-symmetric (-1.28%).

Table 1. Symmetry Index (SI) distributions for vertical GRFs during leftward and rightward jumps.

Jump Direction	GRF Value	SI Trend	Number of Participants	SI Range [%]	Interpretation
Leftward	Maximum	Negative	19	−0.47 to −59.41	Higher vertical force in right/dominant limb
	Maximum	Positive	2	1.49 to 7.77	Slightly higher force in left/non-dominant limb
	Minimal	Positive	19	23.08 to 102.41	Greater force absorption in left/non-dominant limb
	Minimal	Negative	1	−1.28	Near symmetry
Rightward	Maximum	Positive	18	3.46 to 17.80	Higher vertical force in left limb
	Maximum	Negative	2	−3.46 to −17.80	Slightly higher force in right limb
	Minimal	Negative	16	−3.29 to −64.85	Greater force absorption in right limb
	Minimal	Positive	4	4.07 to 15.36	Slightly higher absorption in left limb

In the rightward jump, two participants exhibited negative SI values for the maximum vertical GRF (-3.46% and -17.80%), while the rest showed positive values, indicating higher force in the left limb. For minimal vertical GRF, 16 participants had negative SI values (-3.29% to -64.85%), reflecting dominant force absorption in the right limb, while four participants had positive SI values (4.07% to 15.36%).

These results demonstrate a direction-dependent asymmetry in vertical GRF: the right/dominant limb generates higher vertical forces during leftward jumps, while the left/non-dominant limb produces higher vertical forces during rightward jumps. Similarly,

the limb opposite to the direction of maximum force tends to absorb more impact, as reflected in the minimal GRF SI distributions.

3.3. The Anterior–Posterior Component of the Ground Reaction Force

During the leftward jump, the maximum anterior–posterior (AP) ground reaction force (GRF) was significantly higher in the right lower limb compared to the left limb (1.06 ± 0.38 vs. 0.69 ± 0.25 N/kg, $p = 0.001$), representing a 53.6% higher force and indicating greater propulsion or control in the right limb (Figure 5A).

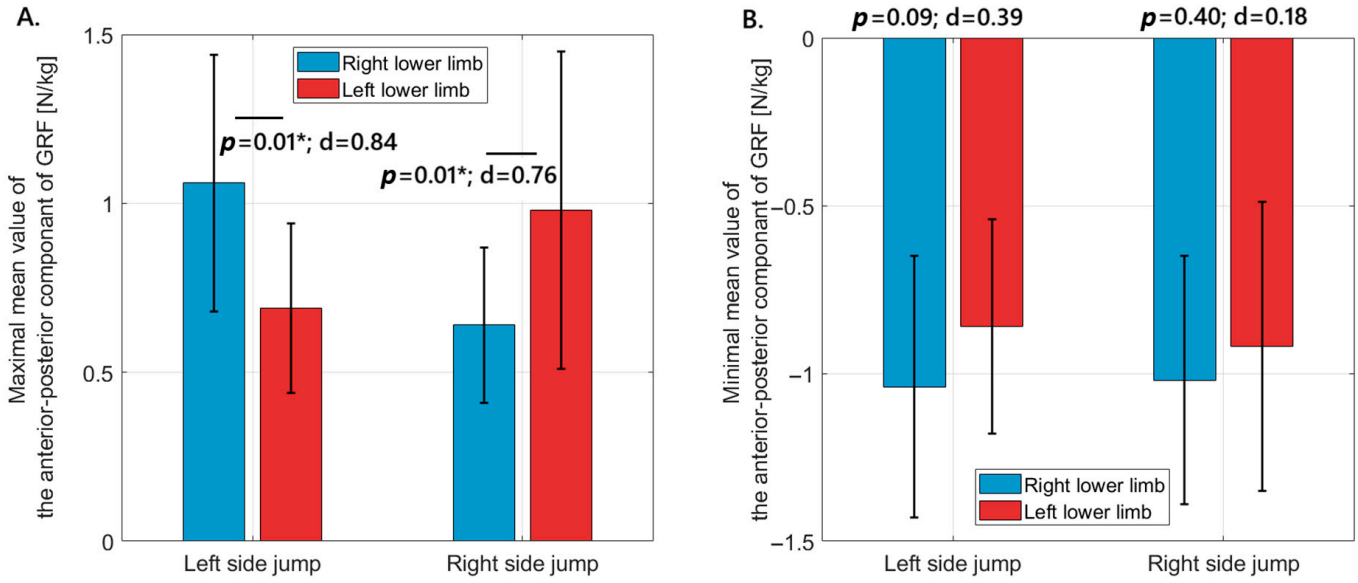


Figure 5. Mean and standard deviation of (**A**) maximal and (**B**) minimal values of the anterior–posterior component of ground reaction force (GRF) during side jumps, shown separately for leftward and rightward jump directions. Values are shown for the dominant (right lower limb) and non-dominant (left lower limb). Statistically significant differences are indicated with an asterisk (*) and reported with the corresponding $p-$values and Cohen's d effect sizes.

For the minimal AP GRF values in the same jump, the left lower limb showed a value of (−0.86 ± 0.32 N/kg), while the right lower limb reached (−1.04 ± 0.39 N/kg). This minimal AP GRF represents the braking force, which is the component of the ground reaction force acting opposite to the direction of motion, helping control the body during take-off. Although this corresponds to a 20.9% more negative GRF for the right lower limb, the difference was not statistically significant, indicating similar braking force behavior between limbs (Figure 5B).

In the rightward jump, the maximum AP GRF was significantly higher in the left limb compared to the right (0.98 ± 0.47 vs. 0.64 ± 0.23 N/kg, $p = 0.002$), representing a 53.1% greater peak force and suggesting stronger propulsion in the left limb (Figure 5A).

For the minimal AP GRF values, the left limb recorded −1.02 ± 0.37 N/kg, while the right limb reached −0.92 ± 0.43 N/kg. Again, this minimal AP GRF indicates the braking force, acting to stabilize the body during take-off. The 9.8% difference was not statistically significant, again showing similar braking forces across limbs (Figure 5B).

Symmetry Index (SI) analysis further illustrates these asymmetries. The distributions of SI values for maximal and minimal AP GRFs are summarized in Table 2.

Table 2. Symmetry Index (SI) distributions for AP GRFs during leftward and rightward jumps.

Jump Direction	GRF Value	SI Trend	Number of Participants	SI Range [%]	Interpretation
Leftward	Maximal	Negative	16	−0.20 to −174.87	Higher AP GRF in right/dominant limb
	Maximal	Positive	4	5.95 to 41.57	Slightly higher AP force in left/non-dominant limb
	Minimal	Negative	14	−9.39 to −82.51	Greater braking in right/dominant limb
	Minimal	Positive	6	10.54 to 120.62	Slightly higher braking in left/non-dominant limb
Rightward	Maximal	Positive	15	5.92 to 126.10	Higher AP force in left limb
	Maximal	Negative	5	−3.70 to −59.24	Slightly higher force in right limb
	Minimal	Positive	11	14.92 to 90.99	Slightly greater braking in left limb
	Minimal	Negative	9	−9.10 to −83.41	Greater braking in right limb

These results reveal a direction-dependent asymmetry in AP GRF: the right/dominant limb generates greater maximal AP GRF during leftward jumps, while the left/non-dominant limb shows higher maximal AP GRF during rightward jumps. Minimal AP GRF values are more balanced, but still reflect a trend toward higher braking forces in the limb opposite the direction of maximal propulsion.

3.4. The Mediolateral Component of the Ground Reaction Force

During the leftward jump, the maximal value of medial–lateral (ML) component of the ground reaction force (GRF) was significantly higher in the left/non-dominant limb compared to the right/dominant limb (0.40 ± 0.10 vs. 0.05 ± 0.30 N/kg, $p = 0.001$), corresponding to a 700% greater force and indicating substantially stronger lateral force production in the left/non-dominant limb (Figure 6A).

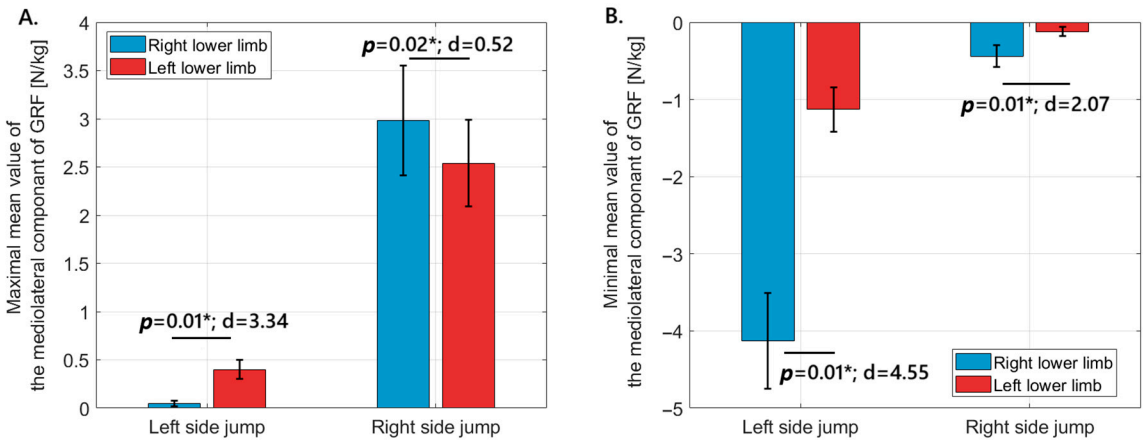


Figure 6. Mean and standard deviation of (**A**) maximal and (**B**) minimal values of the mediolateral component of ground reaction force (GRF) during side jumps, shown separately for leftward and rightward jump directions. Values are shown for the dominant (right lower limb) and non-dominant (left lower limb). Statistically significant differences are indicated with an asterisk (*) and reported with the corresponding $p-$values and Cohen's d effect sizes.

For the minimal ML GRF values in the same jump, the right/dominant limb showed a significantly more negative force (−4.13 ± 0.62 N/kg) compared to the left/non-dominant limb (−1.13 ± 0.29 N/kg; $p = 0.01$), representing a 265.5% greater medial braking force in the right/dominant limb, which is the force that opposes lateral motion and slows down the limb to maintain stability during directional changes (Figure 6B).

In the rightward jump, the maximal ML GRF was significantly higher in the right/dominant limb compared to the left/non-dominant limb (2.98 ± 0.57 vs. 2.54 ± 0.45 N/kg, $p = 0.02$), corresponding to a 17.3% increase and reflecting stronger lateral push in the right/dominant limb (Figure 6A). For the minimal values, the right/dominant limb again demonstrated a significantly more negative force (−0.44 ± 0.14 vs. −0.12 ± 0.06 N/kg;

$p = 0.001$), representing a 266.7% greater medial braking force compared to the left/non-dominant limb (Figure 6B).

Symmetry Index (SI) analysis highlights the direction-dependent asymmetry of ML forces. The distributions of SI values are summarized in Table 3.

Table 3. Symmetry Index (SI) distributions for ML GRF during leftward and rightward jumps.

Jump Direction	GRF Value	SI Trend	Number of Participants	SI Range [%]	Interpretation
Leftward	Maximum	Positive	20	87.25 to 185.19	Higher lateral force in left/non-dominant limb
	Minimal	Negative	20	−77.14 to −155.37	Greater medial braking in right/dominant limb
Rightward	Maximal	Positive	7	0.16 to 62.13	Slightly higher lateral force in left limb
	Maximal	Negative	13	−1.35 to −79.67	Higher lateral force in right limb
	Minimal	Negative	20	−22.14 to −199.72	Greater medial braking in right limb

These results reveal a strong direction-dependent asymmetry in ML GRF. During leftward jumps, the left lower limb produces substantially higher lateral forces, while the right lower limb consistently experiences greater medial braking forces, which slow lateral motion to stabilize the take-off and maintain balance. In rightward jumps, lateral force production is generally higher in the right lower limb, although maximal SI values show some individual variability. Minimal ML forces consistently indicate stronger medial braking forces in the right lower limb across participants.

3.5. Correlation Analysis Between Knee Muscle Torque Values and GRF Symmetry Indices

Correlation analyses were performed to examine the relationships between knee muscle torque (extension and flexion for both right and left lower limbs) and the symmetry indices (SIs) of ground reaction forces (GRFs) in the medial–lateral (ML), anterior–posterior (AP), and vertical (PD) directions, considering both maximal and minimal values.

For the leftward jump, no correlations reached statistical significance. The strongest trends were observed between left knee flexor torque and SI of maximal AP GRF ($r = 0.429$, $p = 0.059$), and between SI of minimal AP GRF and extension torque symmetry ($r = -0.364$, $p = 0.115$). All other correlations were small to moderate (ranging from −0.273 to 0.354) and non-significant ($p > 0.126$), suggesting that isolated measures of knee extension or flexion torque do not robustly explain inter-limb asymmetries in GRF during this movement. Overall, these results indicate that, for the leftward jump, asymmetries in ground reaction forces are largely independent of knee torque differences.

In contrast, for the rightward jump, several significant associations emerged. Maximal ML SI was positively correlated with left knee flexor torque ($r = 0.545$, $p = 0.013$), indicating that greater left flexor strength was associated with higher ML force asymmetry. Maximal AP SI also showed a positive correlation with left knee flexor torque ($r = 0.493$, $p = 0.027$), suggesting that left flexor strength contributes to anterior–posterior force asymmetry. Additionally, minimal AP SI was positively correlated with right knee extensor torque ($r = 0.492$, $p = 0.028$), indicating that stronger right extensors were linked to greater asymmetry in AP braking forces. Other correlations were small to moderate and did not reach significance, implying that knee muscle torque only partially explains inter-limb differences in GRF symmetry during the rightward jump. Taken together, these findings highlight a functional link between knee muscle torque and directional asymmetries in GRF, particularly in the ML and AP components.

4. Discussion

This study evaluated asymmetries in knee joint muscle torque and ground reaction forces (GRFs) during side jumps in young, healthy females with right lower limb dominance. The results revealed consistent asymmetries in favor of the dominant limb across

both static (isometric torque) and dynamic (GRF) variables. These direction-dependent neuromuscular patterns reinforce previous findings on lateral movement biomechanics and limb dominance [14,28], with implications for understanding performance mechanics and asymmetry-related risk factors. While asymmetries of smaller magnitude or different directional patterns have been reported in sagittal-plane jumps (e.g., vertical and forward jumps) [29–31], the present findings demonstrate that mediolateral tasks impose unique demands on limb coordination and loading. This contrast underscores the novelty of the present work in addressing an underexplored movement plane. Although potential relevance for applied settings exists, the present dataset does not allow for direct translation into training recommendations, and such applications should be interpreted with caution.

4.1. Relationship Between Knee Muscle Torque and Vertical Component of GRF

Significantly greater torque in both knee extensors and flexors was exhibited by the dominant (right) limb, in alignment with prior studies showing that limb dominance is often associated with superior strength due to neuromuscular adaptation from habitual use [32]. This strength asymmetry was mirrored by the GRF data, in which the dominant limb (right) was observed to produce significantly higher vertical forces during leftward jumps.

Vertical GRF is primarily influenced by the concentric activity of the knee extensors during take-off [33]. Therefore, the observed torque dominance in the right leg likely enabled greater vertical propulsion, consistent with findings that link leg strength to jump performance and force output [34]. In this study, these relationships were identified under standardized laboratory conditions, which, while ensuring measurement consistency, may not fully capture the variability and demands of competitive or unpredictable environments. Support for the observed higher vertical GRFs in the dominant limb is provided indirectly by a systematic review by Babić et al. [35], in which greater lower-limb power was found to correlate with elevated anaerobic performance biomarkers.

During landing, greater minimal vertical GRF was also shown by the dominant limb, suggesting a stronger shock absorption role, likely facilitated by higher eccentric control from the flexor muscles. The critical role of eccentric hamstring activity in reducing impact forces and stabilizing the knee joint has been shown previously [2].

4.2. Relationship Between Knee Muscle Torque and Anterior–Posterior Component of GRF

Anterior–posterior GRF asymmetries were found to follow a similar direction-dependent pattern. During leftward jumps, the right limb was observed to produce a 53.6% higher peak AP force, underscoring its dominant role in forward propulsion. This finding is corroborated by previous reports identifying the right leg as the main contributor to forward momentum in lateral movements [36].

The link between knee extensor torque and AP GRF is understood to reflect fundamental movement mechanics, whereby the ability to generate horizontal force is contingent on lower-limb power and strength, especially at the knee [37]. Furthermore, more stable and consistent propulsive patterns are typically produced by a stronger limb, which can facilitate smoother and more efficient direction changes [38].

The trend in braking (negative AP) forces suggests that stronger knee flexors assist in deceleration, consistent with evidence showing the crucial role of eccentric muscle control in effective stopping and cutting actions [39].

The correlation analyses reported above support these findings, showing significant associations between right knee extensor torque and minimal AP GRF SI, and left knee flexor torque with maximal AP GRF SI, indicating that knee torque contributes to the magnitude of AP asymmetries in direction-specific jumps.

As with the vertical GRF findings, the AP force data were collected under standardized and predictable laboratory conditions. While measurement reliability is improved by such conditions, variability in inter-limb force generation patterns that might emerge in randomized or ecologically valid settings may not be captured fully.

4.3. Relationship Between Knee Muscle Torque and Mediolateral Component of GRF

In contrast to vertical and AP GRFs, a functional dichotomy was observed in mediolateral GRFs: lateral propulsion was primarily generated by the leading limb, while medial braking was handled by the right limb. Despite lower torque, a higher lateral force was generated by the leading limb, suggesting that muscles other than the knee extensors, such as the hip abductors and ankle evertors, play a prominent role in mediolateral force production [40]. Meanwhile, consistently higher medial braking forces were generated by the right limb, likely facilitated by its superior flexor strength. Hamstring activation during side-stepping has been shown to stabilize lateral knee motion and absorb transverse-plane forces [41,42]. Correlation results additionally showed that left knee flexor torque was significantly associated with maximal ML SI during rightward jumps ($r = 0.545$, $p = 0.013$), highlighting a link between knee flexor strength and mediolateral asymmetry, particularly for jumps toward the dominant (right) side.

This observation aligns with evidence indicating that hip abductors, particularly the gluteus medius, contribute substantially to mediolateral stability and propulsion [43]. Weakness or delayed activation of these muscles can be associated with exacerbation of asymmetries by shifting load demands toward distal joints, thereby potentially increasing ankle or knee injury risk. It is recommended that future studies quantify hip and ankle kinetics to fully map the inter-joint coordination underlying ML asymmetry.

Importantly, the finding that the limb positioned opposite to the direction of travel (commonly referred to as the trailing limb) produces greater propulsive forces, while the leading limb is more engaged in braking, mirrors functional demands observed in sport-specific actions such as cutting, side-stepping, and deceleration tasks. In these contexts, efficient propulsion by the trailing limb and effective braking by the leading limb are critical for maintaining speed, balance, and readiness for subsequent movements [31]. Such parallels suggest that the asymmetrical strategies identified here may have direct implications for performance optimization and injury prevention in multidirectional sports.

These findings highlight the complexity of lateral movements, in which strength alone does not determine limb role; rather, task-specific coordination among joints is believed to influence movement outcomes [44].

4.4. Limb Specialization and Neuromechanical Strategy in Lateral Movement

The observed asymmetries are interpreted as evidence of a functional specialization strategy, in which each limb fulfills different neuromechanical roles based on its capabilities. Greater torque production is demonstrated by the dominant leg, enabling it to act as the primary force generator and absorber, whereas the non-dominant leg contributes to lateral propulsion and stabilization. This pattern is consistent with the concept of "limb differentiation" in dynamic tasks, a phenomenon supported by clinical and athletic literature [14]. Although such specialization may be beneficial for movement efficiency, it may also predispose individuals to injury if compensatory strategies overburden one limb [28]. The asymmetrical loading observed in lateral movements is particularly relevant to female athletes, who exhibit a higher incidence of knee injuries such as ACL ruptures [2]. In contrast to sagittal-plane movements, in which limb contributions are often more symmetrical [29], lateral tasks appear to magnify functional divergence, highlighting the importance of movement-plane-specific assessments. While practical implications are conceivable, the

present results should be interpreted primarily in a biomechanical research context rather than as prescriptive training guidance.

4.5. Practical Implications for Training and Rehabilitation

The importance of addressing neuromuscular asymmetries in both strength and functional movement patterns is underscored by the present findings, to optimize athletic performance and reduce injury risk. Specifically, dominance-related discrepancies in muscle torque and ground reaction forces highlight the need for targeted bilateral strength training, with particular emphasis placed on strengthening the non-dominant limb's knee extensors and flexors to restore muscular balance [1]. Symmetry in force production may be improved, and compensatory overuse of the dominant side, associated with elevated injury risk, may be reduced by strengthening the weaker limb.

Additionally, eccentric training of the hamstring muscles is recommended to enhance the lower limb's ability to absorb shock and control deceleration during landing phases, a key factor in reducing anterior cruciate ligament (ACL) injury risk [2].

Stronger eccentric hamstring function is expected to support better braking control, particularly in the trailing limb, which handles a significant portion of medial and vertical impact forces. In lateral jumps, the trailing limb is generally the leg positioned opposite to the direction of travel, playing a primary role in generating propulsion and absorbing forces during take-off.

Given the potential role of hip abductors in mediolateral propulsion and braking, the inclusion of exercises such as side-lying hip abduction, band-resisted lateral walks, and single-leg lateral step-downs is recommended to address proximal control deficits [43,45]. For integrating strength into dynamic contexts, lateral bounding with controlled landings and crossover step drills may be utilized to enhance both force generation and stability.

Neuromuscular coordination drills, such as agility ladder work, side shuffles, or lateral bounding, should be incorporated to improve control during lateral movements. The ability of the leading limb to stabilize the body and maintain balance during deceleration and change-of-direction tasks may be improved by these exercises [46]. Enhancing neuromuscular efficiency in such movements is considered particularly important for injury prevention in sports requiring rapid directional shifts.

Lastly, routine screening of GRF and torque asymmetries during jumping or movement assessments is suggested as a valuable tool for identifying athletes at higher injury risk. Individualized training and rehabilitation protocols may be informed by such evaluations, enabling progress to be monitored and the re-emergence of imbalances to be prevented following injury [47,48]. By proactively addressing these asymmetries, athletes can be better prepared for the demands of sport, and their susceptibility to lower limb injuries can be reduced.

4.6. Limitations and Future Research

Several limitations of the present study should be acknowledged to guide interpretation and inform future research directions. First, the sample consisted exclusively of young, healthy, and right-limb-dominant females, which limits the generalizability of the findings. It is plausible that sex-, limb-dominance-, and age-related neuromuscular differences could influence the observed patterns of asymmetry. Therefore, extending research to include males, left-dominant individuals, and older populations would enhance the applicability of the results across diverse athletic and clinical groups. Second, the study assessed only isometric torque at the knee joint, which, while valuable, does not capture the full spectrum of muscular function during dynamic activities. Incorporating dynamic strength evaluations, such as isokinetic testing or sport-specific functional strength tests, could

provide a more comprehensive understanding of muscular contributions to movement asymmetries. Third, muscle activity from adjacent joints, particularly the hip and ankle, was not measured, although these joints likely play crucial roles in ground reaction force generation and absorption during lateral movements. Excluding these components may underestimate the complexity of inter-joint coordination involved in such tasks. Fourth, all tests were performed in a controlled, predictable laboratory setting, which may not accurately replicate competitive or unpredictable conditions where movement biases might be more pronounced.

To build on these findings, future research should:

- Include larger and more heterogeneous participant groups, incorporating both sexes, various age categories, and different dominance profiles;
- Integrate dynamic and multi-joint strength assessments, alongside kinetic and kinematic analyses, to capture a broader spectrum of neuromuscular contributions;
- Employ randomized task orders and varied movement conditions to reduce anticipatory adaptations;
- Design testing environments that simulate competitive constraints to better reveal functional asymmetries under realistic performance stressors.

Additionally, future studies should focus on multi-joint kinetic analyses and electromyographic (EMG) assessments to capture the full neuromuscular strategy employed during lateral movements. Intervention-based research is also needed to evaluate the effectiveness of targeted training programs in reducing strength and force asymmetries. Finally, longitudinal investigations tracking the development and resolution of asymmetries over time, particularly in athletes and clinical populations recovering from injury, could yield critical insights into injury risk mitigation and performance optimization.

5. Conclusions

In conclusion, this study demonstrates a clear biomechanical relationship between knee muscle torque asymmetries and ground reaction force asymmetries during lateral jumps, which are significantly influenced by jump direction and limb dominance. The dominant limb's enhanced knee extensor and flexor torque enables greater propulsive and absorptive forces, predominantly by the trailing leg, while the leading leg primarily supports lateral stabilization and braking. This limb-specific functional specialization highlights the complexity of neuromuscular control in lateral movements and emphasizes the importance of comprehensive, multi-planar assessment in both athletic and clinical contexts.

Addressing strength and kinetic asymmetries through targeted training and rehabilitation may improve lateral movement efficiency, reduce injury risk, and improve return-to-sport outcomes. Practitioners should incorporate lateral jumping tasks and symmetry assessments as standard components in performance evaluation and recovery protocols. However, because the present sample consisted solely of right-limb-dominant females, the generalizability of these findings to males, left-dominant individuals, or athletes from different sports and skill levels is limited. Replication in broader and more varied populations is recommended to confirm and expand upon these observations.

From a clinical perspective, the integration of force plate asymmetry readings into standard screening procedures could provide objective benchmarks for limb function. For example, mediolateral and vertical force asymmetry thresholds could inform return-to-sport readiness following anterior cruciate ligament (ACL) reconstruction, ensuring that both propulsive and braking capacities are restored before full competition is resumed.

Future studies involving more diverse populations and employing dynamic neuromuscular assessments will further elucidate the intricate relationships governing lateral move-

ment biomechanics. Given the study's methodological limitations, these findings should be regarded as exploratory rather than directly prescriptive for training or injury prevention.

Author Contributions: Conceptualization, M.B., A.M. and M.T.; methodology, M.B.; software, M.B., A.M. and M.T.; validation, M.S. and J.W.; formal analysis, M.B. and J.W.; investigation, M.B., A.M. and M.T.; resources, M.S. and J.W.; data curation, M.B., A.M. and M.T.; writing—original draft preparation, M.B. and J.W.; writing—review and editing, M.B. and J.W.; visualization, M.B. and J.W.; supervision, M.B. and J.W.; project administration, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of Józef Piłsudski University of Physical Education in Warsaw, Poland (protocol code: SKE01-15/2023; date of approval: 24 March 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to ongoing data collection and further research being conducted on this topic.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dos'Santos, T.; Thomas, C.; Comfort, P.; Jones, P.A. The Effect of Training Interventions on Change of Direction Biomechanics Associated with Increased Anterior Cruciate Ligament Loading: A Scoping Review. *Sports Med.* **2019**, *49*, 1837–1859. [CrossRef]
2. Mirkov, D.M.; Nedeljkovic, A.; Milanovic, S.; Jaric, S. Muscle strength testing: Evaluation of tests of explosive force production. *Eur. J. Appl. Physiol.* **2004**, *91*, 147–154. [CrossRef] [PubMed]
3. Góra, T.; Mosler, D.; Ortenburger, D.; Wąsik, J. Sex differences in utilizing effective mass among taekwon-do athletes performing turning and side kick. *Phys. Act. Rev.* **2024**, *12*, 78–85. [CrossRef]
4. Kędziorek, J.; Błażkiewicz, M.; Wąsik, J.; Szopa, J.; Sołdacka, A. Reaction Time and Postural Control Under Dual-Task Conditions in Brazilian Jiu-Jitsu Athletes. *Appl. Sci.* **2025**, *15*, 3877. [CrossRef]
5. McCurdy, K.W.; Langford, G.A.; Doscher, M.W.; Wiley, L.P.; Mallard, K.G. The effects of short-term unilateral and bilateral lower-body resistance training on measures of strength and power. *J. Strength Cond. Res.* **2005**, *19*, 9–15. [CrossRef]
6. Hewett, T.E.; Myer, G.D.; Ford, K.R. Reducing knee and anterior cruciate ligament injuries among female athletes: A systematic review of neuromuscular training interventions. *J. Knee Surg.* **2005**, *18*, 82–88. [CrossRef]
7. Marián, V.; Katarína, L.; Dávid, O.; Matúš, K.; Simon, W. Improved Maximum Strength, Vertical Jump and Sprint Performance after 8 Weeks of Jump Squat Training with Individualized Loads. *J. Sports Sci. Med.* **2016**, *15*, 492–500.
8. Petrigna, L.; Karsten, B.; Marcolin, G.; Paoli, A.; D'Antona, G.; Palma, A.; Bianco, A. A Review of Countermovement and Squat Jump Testing Methods in the Context of Public Health Examination in Adolescence: Reliability and Feasibility of Current Testing Procedures. *Front. Physiol.* **2019**, *10*, 1384. [CrossRef]
9. Huang, H.; Huang, W.-Y.; Wu, C.-E. The Effect of Plyometric Training on the Speed, Agility, and Explosive Strength Performance in Elite Athletes. *Appl. Sci.* **2023**, *13*, 3605. [CrossRef]
10. Bartosz, M.; Latocha, A.; Motowidło, J.; Krzysztofik, M.; Zajac, A. The relationship between countermovement jump performance and sprinting speed in elite sprinters. *Phys. Act. Rev.* **2024**, *12*, 29–37. [CrossRef]
11. Zwierko, M.; Jedziniak, W.; Popowczak, M.; Rokita, A. Effects of six-week stroboscopic training program on visuomotor reaction speed in goal-directed movements in young volleyball players: A study focusing on agility performance. *BMC Sports Sci. Med. Rehabil.* **2024**, *16*, 59. [CrossRef]
12. Blazek, D.; Pisz, A.; Hojka, V.; Uhlir, P.; Kolinger, D.; Zajac, A.; Stastny, P. The bench press prime mover muscles firing frequency changes according to sticking region during maximal and submaximal effort. *Phys. Act. Rev.* **2024**, *14*, 150. [CrossRef]
13. Kędziorek, J.; Błażkiewicz, M. Influence of the base of support widths on postural control and feet loading symmetry during squat—Preliminary study. *Acta Bioeng. Biomech.* **2022**, *24*, 55–63. [CrossRef]
14. Impellizzeri, F.M.; Bizzini, M.; Rampinini, E.; Cereda, F.; Maffiuletti, N.A. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. *Clin. Physiol. Funct. Imaging* **2008**, *28*, 113–119. [CrossRef]
15. Gulatowska, M.; Błażkiewicz, M. The Effect of Repetitive Mechanical Perturbations on Lower Limb Symmetry in Postural Control. *Symmetry* **2025**, *17*, 245. [CrossRef]

16. Sadeghi, H.; Allard, P.; Prince, F.; Labelle, H. Symmetry and limb dominance in able-bodied gait: A review. *Gait Posture* **2000**, *12*, 34–45. [CrossRef] [PubMed]
17. Bishop, C.; Turner, A.; Read, P. Effects of Inter-limb Asymmetries on Physical and Sports Performance: A Systematic Review. *J. Sports Sci.* **2017**, *36*, 1135–1144. [CrossRef] [PubMed]
18. Kobayashi, Y.; Kubo, J.; Matsubayashi, T.; Matsuo, A.; Kobayashi, K.; Ishii, N. Relationship between bilateral differences in single-leg jumps and asymmetry in isokinetic knee strength. *J. Appl. Biomech.* **2013**, *29*, 61–67. [CrossRef]
19. Robinson, R.O.; Herzog, W.; Nigg, B.M. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *J. Manip. Physiol. Ther.* **1987**, *10*, 172–176.
20. Hart, N.H.; Nimphius, S.; Spiteri, T.; Newton, R.U. Leg strength and lean mass symmetry influences kicking performance in Australian football. *J. Sports Sci. Med.* **2014**, *13*, 157–165. [PubMed]
21. Prończuk, M.; Skalski, D.; Zak, M.; Motowidło, J.; Markowski, J.; Pilch, J.; Kostrzewa, M.; Tsos, A.; Maszczyk, A. The influence of EEG-biofeedback training and Beta waves in normoxia and normobaric hypoxia on the bench press in judo athletes. *Phys. Act. Rev.* **2024**, *12*, 65–77. [CrossRef]
22. Dahab, K.S.; McCambridge, T.M. Strength training in children and adolescents: Raising the bar for young athletes? *Sports Health* **2009**, *1*, 223–226. [CrossRef]
23. Hadamus, A.; Błażkiewicz, M.; Wydra, K.T.; Kowalska, A.J.; Łukowicz, M.; Białoszewski, D.; Marczyński, W. Effectiveness of Early Rehabilitation with Exergaming in Virtual Reality on Gait in Patients after Total Knee Replacement. *J. Clin. Med.* **2022**, *11*, 4950. [CrossRef]
24. Hadamus, A.; Błażkiewicz, M.; Kowalska, A.J.; Wydra, K.T.; Grabowicz, M.; Łukowicz, M.; Białoszewski, D.; Marczyński, W. Nonlinear and Linear Measures in the Differentiation of Postural Control in Patients after Total Hip or Knee Replacement and Healthy Controls. *Diagnostics* **2022**, *12*, 1595. [CrossRef]
25. Promsri, A.; Haid, T.; Federolf, P. How does lower limb dominance influence postural control movements during single leg stance? *Hum. Mov. Sci.* **2018**, *58*, 165–174. [CrossRef]
26. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*; Lawrence Erlbaum Assiociates: New York, NY, USA, 1988.
27. Błażkiewicz, M.; Wiszomirska, I.; Wit, A. Comparison of four methods of calculating the symmetry of spatial-temporal parameters of gait. *Acta Bioeng. Biomech.* **2014**, *16*, 29–35. [PubMed]
28. Bishop, C.; Turner, A.; Gonzalo-Skok, O.; Read, P. Inter-limb Asymmetry during Rehabilitation: Understanding Formulas and Monitoring the "Magnitude" and "Direction". *Aspetar Sports Med. J.* **2020**, *9*, 18–22.
29. Lecce, E.; Del Vecchio, A.; Nuccio, S.; Felici, F.; Bazzucchi, I. Higher dominant muscle strength is mediated by motor unit discharge rates and proportion of common synaptic inputs. *Sci. Rep.* **2025**, *15*, 8269. [CrossRef] [PubMed]
30. Zifchock, R.A.; Davis, I.; Higginson, J.; Royer, T. The symmetry angle: A novel, robust method of quantifying asymmetry. *Gait Posture* **2008**, *27*, 622–627. [CrossRef]
31. Aizawa, J.; Hirohata, K.; Ohji, S.; Ohmi, T.; Yagishita, K. Limb-dominance and gender differences in the ground reaction force during single-leg lateral jump-landings. *J. Phys. Ther. Sci.* **2018**, *30*, 387–392. [CrossRef]
32. Sañudo, B.; Sánchez-Hernández, J.; Bernardo-Filho, M.; Abdi, E.; Taiar, R.; Núñez, J. Integrative Neuromuscular Training in Young Athletes, Injury Prevention, and Performance Optimization: A Systematic Review. *Appl. Sci.* **2019**, *9*, 3839. [CrossRef]
33. Fort-Vanmeerhaeghe, A.; Romero-Rodríguez, D.; Lloyd, R.; Kushner, A.; Myer, G. Integrative Neuromuscular Training in Youth Athletes. Part II: Strategies to Prevent Injuries and Improve Performance. *Strength Cond. J.* **2016**, *38*, 9–27. [CrossRef]
34. Carpes, F.P.; Mota, C.B.; Faria, I.E. On the bilateral asymmetry during running and cycling—A review considering leg preference. *Phys. Ther. Sport* **2010**, *11*, 136–142. [CrossRef]
35. Winter, D.A. Human balance and posture control during standing and walking. *Gait Posture* **1995**, *3*, 193–214. [CrossRef]
36. Markovic, G.; Mikulic, P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med.* **2010**, *40*, 859–895. [CrossRef]
37. Babić, M.; Pobrić, I.; Čular, D. Physiological response and biomarkers in kickboxing -systematic review. *Phys. Act. Rev.* **2023**, *11*, 2023. [CrossRef]
38. Xergia, S.; Tsepis, E.; Georgoulis, A.; Tsarbou, C.; Liveris, N.; Pappas, E. Association between hop tests and self-reported knee function in patients after anterior cruciate ligament reconstruction. *Arch. Hell. Med./Arheia Ellenikes Iatr.* **2024**, *24*, 475–480.
39. Thomas, C.; Comfort, P.; Chiang, C.-Y.; Jones, P. Relationship between isometric mid-thigh pull variables and sprint and change of direction performance in collegiate athletes. *J. Trainol.* **2015**, *4*, 6–10. [CrossRef] [PubMed]
40. Dai, B.; Mao, M.; Garrett, W.; Yu, B. Biomechanical characteristics of an anterior cruciate ligament injury in javelin throwing. *J. Sport Health Sci.* **2015**, *42*, 333–340. [CrossRef]
41. McLean, S.G.; Huang, X.; van den Bogert, A.J. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clin. Biomech. (Bristol. Avon.)* **2005**, *20*, 863–870. [CrossRef] [PubMed]
42. Claiborne, T.; Armstrong, C.; Gandhi, V.; Pincivero, D. Relationship between Hip and Knee Strength and Knee Valgus during a Single Leg Squat. *J. Appl. Biomech.* **2006**, *22*, 41–50. [CrossRef]

43. Besier, T.F.; Lloyd, D.G.; Cochrane, J.L.; Ackland, T.R. External loading of the knee joint during running and cutting maneuvers. *Med. Sci. Sports Exerc.* **2001**, *33*, 1168–1175. [CrossRef]
44. Hollman, J.H.; Ginos, B.E.; Kozuchowski, J.; Vaughn, A.S.; Krause, D.A.; Youdas, J.W. Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *J. Sport Rehabil.* **2009**, *18*, 104–117. [CrossRef] [PubMed]
45. Comfort, P.; Jones, P.A.; Smith, L.C.; Herrington, L. Joint Kinetics and Kinematics During Common Lower Limb Rehabilitation Exercises. *J. Athl. Train.* **2015**, *50*, 1011–1018. [CrossRef]
46. Distefano, L.J.; Blackburn, J.T.; Marshall, S.W.; Padua, D.A. Gluteal muscle activation during common therapeutic exercises. *J. Orthop. Sports Phys. Ther.* **2009**, *39*, 532–540. [CrossRef] [PubMed]
47. Acar, H.; Eler, N. The Effect of Balance Exercises on Speed and Agility in Physical Education Lessons. *Univers. J. Educ. Res.* **2019**, *7*, 74–79. [CrossRef]
48. Bailey, C.A.; Sato, K.; Burnett, A.; Stone, M.H. Force-production asymmetry in male and female athletes of differing strength levels. *Int. J. Sports Physiol. Perform.* **2015**, *10*, 504–508. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.