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Interlimb Biomechanics of Female Football Players during Vertical Jump as a Predictor of Anterior Cruciate Ligament Ruptures

Zeynep Katircioglu[1], Begum Yalcin[1], Anil Isik[2], Melda Pelin Yargic[3], Hande Argunsah[1*]

[1]Department of Biomedical Engineering, Faculty of Engineering and Natural Sciences, Acibadem University, Istanbul, Turkey
[2]Acibadem Sports, Sports Medicine Center, Istanbul, Turkey
[3]Romatem Physical Therapy and Rehabilitation Hospital, Sports Medicine Department, Bursa, Turkey
[*]Corresponding author: Hande Argunsah, Department of Biomedical Engineering, Faculty of Engineering and Natural Sciences, Acibadem University, Istanbul, Turkey, e-mail address: hande.argunsah@gmail.com

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Abstract

Purpose: This study investigates inter-limb asymmetry during drop vertical jumps in elite female football players by examining biomechanical variables—such as joint kinematics and ground reaction forces—that are strongly associated with increased anterior cruciate ligament injury risk.

Methods: Kinematic and kinetic parameters of 12 football players performing a vertical drop jump from a 30 cm high box were recorded using the Xsens MVN Awinda motion capture system and Vald Force Decks.

Results: The findings revealed significant differences in range of motion between the limbs, particularly in internal/external rotation and dorsiflexion/plantarflexion ($p < 0.05$). No significant differences were found in abduction/adduction or flexion-extension ROM between limbs during both landing phases. Internal/external rotation range differed significantly during the first landing phase ($p < 0.05$) but not the second. Hip joint flexion/extension exhibited minimal variation compared to the ankle and knee, with slight increases observed at the hip. From a kinetic standpoint, concentric mean power demonstrated a strong positive correlation with peak power ($\rho = 0.903$), underscoring its crucial role in optimizing performance and mitigating injury risk.

Conclusions: The study evaluated biomechanical indicators strongly linked to ACL injury risk. Findings highlight that asymmetrical loading and movement patterns—especially knee valgus and inter-limb discrepancies—may predispose female athletes to non-contact ACL injuries. These results emphasize the need for neuromuscular training interventions targeting symmetry, proprioception, and controlled landing to reduce injury risk and enhance performance.

Keywords: Inter-limb asymmetry; drop vertical jump; Anterior cruciate ligament injury; risk assessment

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1. Introduction

Football's high-impact movements are associated with an increased risk of injury, particularly in the lower extremities, which account for 68% to 88% of these injuries [17]. Elite female football players are at an even greater risk due to their unique physiological and biomechanical characteristics, such as joint laxity and different muscle activation patterns compared to their male counterparts, which make them more susceptible to injury, especially in high-impact sports [9].

Inter-limb asymmetry, resulting from variations in limb strength and function, can increase the risk of injury [4]. This asymmetry can lead to unilateral lower limb injuries like ankle sprains, patellar tendinopathy, ACL injuries, and chronic ankle instability by placing excessive load on one limb. The specialized movements and repetitive nature of football, such as using the stronger foot during shooting, create power and balance asymmetries between the dominant and non-dominant legs. These discrepancies can compromise dynamic performance and increase injury risk, affecting both injury prevention and athletic performance [3], [7], [11], [13], [15], [19]. The relationship between inter-limb asymmetry and injuries in football players has been explored in previous studies [17]- [21]. In elite female athletes, balanced limb function is essential for optimizing performance and reducing injury risk. The Drop Vertical Jump (DVJ) is a commonly used tool to assess lower extremity injury risk by analyzing kinematic and kinetic factors, particularly asymmetries in force production. The DVJ is widely used in biomechanical assessments of ACL injury risk due to its ability to simulate real-world landing mechanics, which are critical in high-impact sports like football. Compared to alternative rebound jump tests such as the 10/5, 5/3, or countermovement rebound jumps, the DVJ is particularly effective in evaluating neuromuscular control, landing kinetics, and kinematic asymmetries, which are key contributors to ACL injury risk. Additionally, previous research has established the DVJ as a validated screening tool for assessing lower limb asymmetries and injury susceptibility, making it a suitable choice for our study [2], [3], [6], [28].

The ACL plays a critical role in knee stability, particularly during deceleration, rapid changes in direction, and landing [7], [19]. ACL injuries in female athletes are predominantly non-contact and often occur during landings from jumps or cutting maneuvers. Biomechanically, these injuries are often caused by excessive anterior tibial translation and shear forces on the ACL, especially during stiff-legged landings where inadequate knee and hip flexion prevent proper hamstring activation to control tibial displacement, leading to increased ACL strain [16], [22].

This study hypothesizes that kinematic and kinetic asymmetries are prevalent in elite athletes, particularly during the initial phases of high-impact activities, and aims to assess the degree of inter-limb symmetry in elite female football players during DVJ. The focus will be on inter-jump impact forces and performance metrics. By analyzing these factors, the study seeks to enhance understanding of how asymmetries in explosive movements affect performance and injury risk. Accordingly, this study aimed to examine interlimb biomechanics during the drop

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vertical jump in elite female football players and to assess these findings in the context of previously identified contributors to ACL injury risk reported in the literature.

2. Materials and Methods

2.1. Participants

Twelve female professional football players (age: 24.4 ± 5.9 years; BMI: 21.09 ± 2.26 kg/m²) from the same professional club in Turkey participated in the study during one competitive season (Table 1). Dominance was determined through self-report, using a brief standardized questionnaire that asked participants to indicate their preferred leg for kicking a ball task. All participants were right side dominant and the dominant side data has been analyzed. Goalkeepers were excluded from the analysis, and participants were not categorized into positional groups to avoid reducing statistical power due to the small sample size within each group. All participants were elite female football players competing at the national level, with an average training experience of 7.2 years and a weekly load of four sessions covering strength, conditioning, tactical, and technical work. Their background ensured familiarity with high-intensity movements relevant to the biomechanical assessments. All participants had no history of lower extremity surgery or serious injury within the past six months. The sample size was determined using G-Power (version 3.2.1, Universität Düsseldorf), ensuring a 95% confidence interval with a two-tailed t-test ($\alpha = 0.05$, power = 0.95, effect size $|\rho| = 0.75$). Ethics committee approval was granted by the Acibadem Mehmet Ali Aydinlar University Institutional Review Board (2020-7/4). Informed consent was obtained from each participant, who was also provided with a thorough briefing on the test procedures.

Table 1. Participant Information

Participant ID	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m²)
P01	24	59.7	165	21.90
P02	32	67.9	175	22.20
P03	19	61.3	168	21.70
P04	29	61.8	168	21.90
P05	22	55.3	168	19.60
P06	31	57.7	163	21.70
P07	18	52.2	162	19.90
P08	17	60.5	171	20.70
P09	29	55.9	163	21.00

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P10	20	67.4	182	20.30
P11	22	65.8	178	19.65
P12	26	59.1	169	17.56

2.2. Experimental Design

The study followed a standardized Drop Vertical Jump (DVJ) technique, involving a bilateral landing from a 30 cm box followed by a maximal vertical jump. Participants received consistent instructions, completed familiarization trials, and were monitored to ensure proper technique execution. The DVJ consists of two distinct phases: (1) the first landing phase, which occurs immediately after stepping off the box and making initial contact with the ground, and (2) the second landing phase, which follows the maximal vertical jump and subsequent re-contact with the ground. To assess the biomechanical characteristics and inter-limb asymmetries during DVJ, kinetic and kinematic data were collected from participants at a FIFA-accredited Sports Athletic Performance Center. The experimental design involved the use of a standard 30 cm box for the DVJ task. For kinematic data collection, the Xsens MVN Awinda (Movella North America Inc., Henderson, NV, USA), a 3D wearable motion capture system, was employed. This system comprises 17 trackers (MTw) attached to specific landmarks on the body, operating on batteries and using wireless communication, sampling data at 60 Hz. Kinetic data were collected using the Vald ForceDecks system (Vald Performance, Brisbane, AU), which consists of two independent force platforms, enabling the simultaneous capture of ground reaction forces for each limb separately. This configuration is particularly suited for analyzing inter-limb asymmetries during bilateral landing tasks such as the DVJ. The system was embedded in the floor and collected data at a sampling rate of 1000 Hz.

Data collection was performed in a single session without a control group. To ensure the consistency of the kinematic and kinetic measurements, test-retest reliability coefficients were calculated from the authors' laboratory. The reliability analysis included the calculation of Intraclass Correlation Coefficients (ICCs) and Standard Error of Measurement (SEM) values. ICC values ranged from 0.85 to 0.92, indicating good to excellent reliability. SEM values, when expressed as a percentage of the grand mean, ranged from 3.2% to 5.6%, reflecting minimal relative measurement error and supporting the consistency of the data across repeated sessions.ICC values indicated good to excellent reliability, with the highest reliability observed

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for ankle dorsiflexion/plantarflexion range of motion during the first landing phase, which was designated as “Kinematic Measure 1” during preliminary analyses.

The participants were equipped with Xsens MVN wireless sensors prior to data collection. They first completed a standardized warm-up protocol and received detailed instructions on the DVJ task. Each piece of equipment was carefully introduced to the participants, and they were thoroughly informed about the purpose and procedures of the study. The warm-up consisted of 5 minutes of light jogging activity on a treadmill, followed by dynamic stretching exercises focusing on the lower extremities (e.g., leg swings, walking lunges, high knees). This protocol was designed to prepare participants for high-impact movements and to replicate a typical pre-training warm-up used in elite football settings.

A standard testing protocol was developed and followed for each participant. Each participant stood atop a 30 cm box with their arms naturally at their sides. The 30 cm height was chosen based on previous research demonstrating its validity in assessing lower limb biomechanics and ACL injury risk. Studies have shown that a 30 cm drop height reliably elicits neuromuscular responses and landing mechanics representative of sport-specific tasks, particularly in female athletes, without introducing excessive variability seen at greater heights (e.g., 40 cm or above) [1]- [3], [5]. The participants were instructed to drop from the box (first landing) and immediately perform a maximal vertical leap (second landing). The task was repeated three times for each participant and the averages of the parameters were analyzed. During the initial drop, participants performed a controlled landing on the force platforms by diving straight down from the box. Upon landing, they executed their highest possible vertical jump, followed by a second landing, where both feet contacted the force platforms again. The DVJ analysis was divided into kinetic and kinematic measurements, with focus on both the first and second landing phases. Kinetic parameters collected during the first landing included jump height, concentric mean power, peak power, peak landing force, eccentric mean force and peak landing force asymmetry. Jump height was estimated using the flight-time method, derived from vertical ground reaction force (vGRF) data recorded by the Vald ForceDecks system. Specifically, the time between take-off and re-landing (when vGRF = 0 N) was used to calculate jump height ($g = 9.81\ m/s^2$). Concentric mean power and peak power were computed automatically via the ForceDecks software. These values were derived from the instantaneous force and velocity signals during the concentric (propulsive) phase of the jump, beginning at the point of minimum center-of-mass displacement and ending at toe-off. Velocity

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was estimated through numerical integration of the acceleration signal, obtained by dividing the net vertical force (after subtracting body weight) by mass. Power was calculated as the product of instantaneous force and velocity, and peak power was defined as the highest value reached during the concentric phase, while mean power was the average over that same interval. The kinetic measures assessed the forces involved during landing and the jump, including the asymmetry between the limbs in force distribution. Kinematic parameters focused on joint movements during the first and second landings, including lower extremity joints' abduction/adduction, internal/external rotation and flexion/extension movements. These joint movements were analyzed to assess the range of motion and potential asymmetries in the lower limbs during both phases of the DVJ. The Xsens MVN Analysis Software (Xsens MVN Record, version 2023.2.0) and MATLAB (Version: R2022b, The MathWorks Inc., Massachusetts, USA) were used to analyze the collected data.

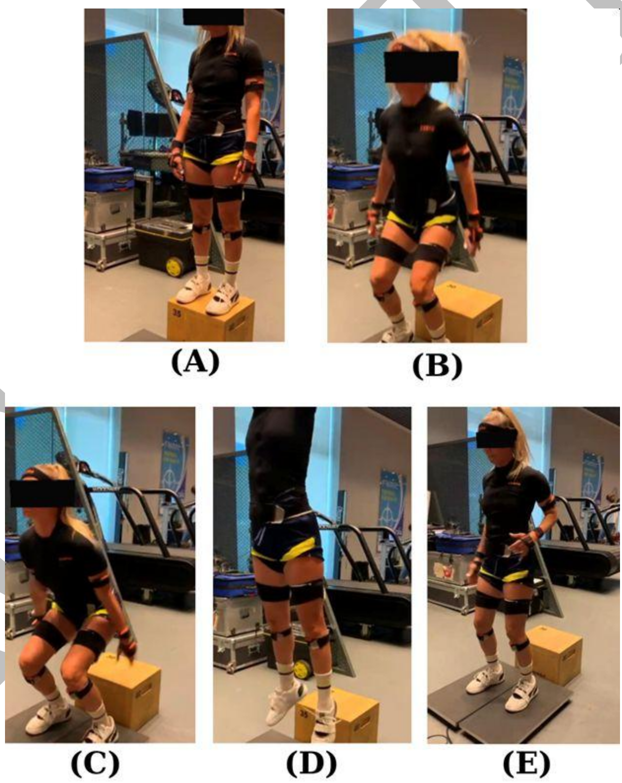

Figure 1. The lower extremity kinematic data were collected with Xsens MVN Awinda (Movella, USA). *(A) standing on a 30 cm box with arms at sides, (B)First Landing (C)Immediate rebound, (D)launch into the highest possible vertical leap, (E) Second Landing*

2.3. Statistical Analyses

Statistical analysis was performed using SPSS (IBM SPSS Statistics 29.0) to evaluate the differences and relationships between the measured variables. Spearman's rho analysis was employed to assess statistical differences in the mean and maximum values of kinetic parameters, including jump height, concentric mean power, peak power, peak landing force, eccentric mean force, and peak landing force asymmetry. This non-parametric test was chosen to examine monotonic relationships between variables, given the nature of the data.

For the kinematic analysis, an independent samples t-test was used to compare side types (right versus left) in terms of ROM across various joints (e.g., ankle, knee, and hip). This comparison allowed for the evaluation of kinematic differences between the dominant and non-dominant limbs. Additionally, a paired samples t-test was applied to assess differences in landing mechanics between the first and second phases of the DVJ. This test helped determine if significant changes occurred in kinematic variables between the two landing phases. To control Type I error, alpha adjustments were applied, with the significance threshold set at $p < 0.05$ for all statistical tests. This ensured that only statistically significant findings were considered, preserving the integrity of the analysis and ensuring that the conclusions drawn were based on reliable data. These statistical methods were essential for evaluating inter-limb asymmetries and biomechanical differences during the DVJ task, contributing to the study's goal of understanding injury risks in female football players.

3. Results

Twelve professional female football players successfully completed the data collection without complications. Participant demographic characteristics (e.g., age, height, weight, BMI) were relatively consistent across individuals, with no substantial outliers or stratification required. The kinematic parameters were compared between the first and second landing phases, while kinetic parameters were reported for the first landing phase. The analysis focused on the interval between initial contact (IC) and the lowest point of the center of mass (COM), examining lower extremity joint movements. Data were averaged over three consecutive jumps for each participant.

3.1. Kinematic Results

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The dashed lines represent the right limb, while the solid lines represent the left limb. The overlapping trajectories of both limbs are shown in Figure 2, with the black dashed and solid lines indicating the mean values, and the gray-shaded areas representing the corresponding 1σ-uncertainties of the trajectories. No significant differences were observed between the right and left ankles in the abduction/adduction, internal/external rotation, and dorsiflexion/plantarflexion actions during the initial landing, according to the independent samples t-test. Similarly, there was no significant distinction between the right and left sides during these ankle movements in the second landing. However, significant differences were found between the right and left ankle internal/external rotation and dorsiflexion/plantarflexion ROM during both the first and second landings ($p < 0.05$) (Fig. 2(a)). The variation in dorsiflexion/plantarflexion patterns was minimal, whereas the variation in internal/external rotation patterns was the largest.

Regarding the knee joint, there were no significant differences in abduction/adduction or flexion-extension ROM between the right and left knees during either landing phase. However, significant differences were noted in internal/external rotation ROM during the first landing ($p < 0.05$), but not during the second landing (Fig. 2 (b)). The variation in hip flexion/extension patterns was minimal compared to the ankle and knee joints but showed a slight increase from the first to the second landing. Similarly, there were no significant differences between the right and left hip in terms of abduction/adduction, internal/external rotation, or flexion-extension ROM during either landing phase. While the variation in hip flexion/extension patterns remained minimal compared to the ankle and knee joints, it showed a noticeable increase during the second landing (Fig. 2(c)).

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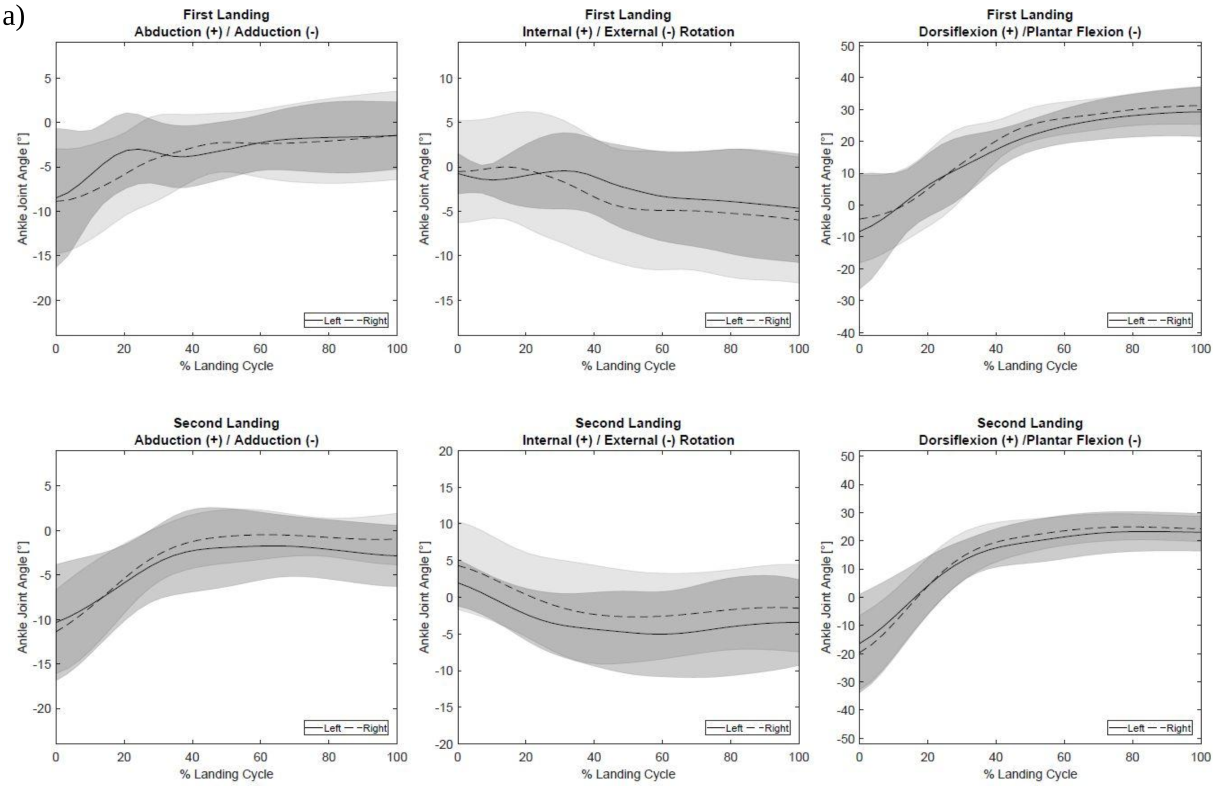
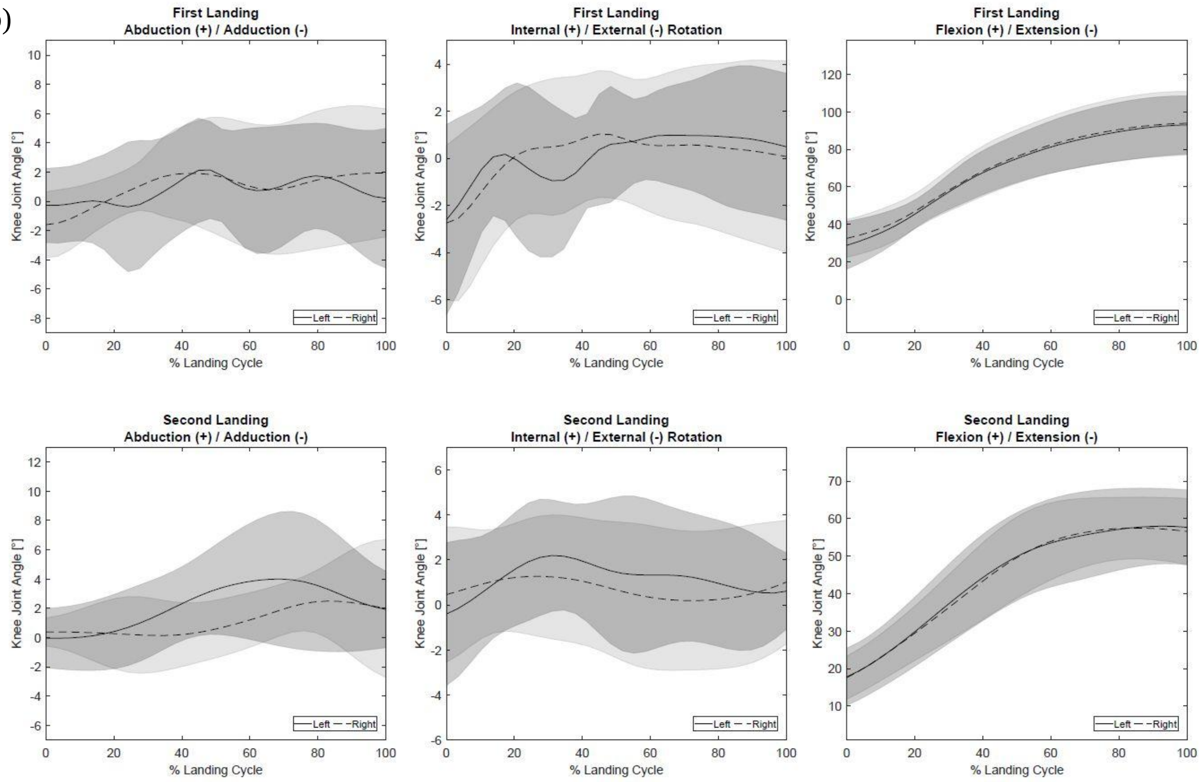
a)


First Landing
Abduction (+) / Adduction (-)
Internal (+) / External (-) Rotation
Dorsiflexion (+) /Plantar Flexion (-)
Second Landing
Ankle Joint Angle [°]
% Landing Cycle
Left
Right

b)


First Landing
Abduction (+) / Adduction (-)
Internal (+) / External (-) Rotation
Flexion (+) / Extension (-)
Second Landing
Knee Joint Angle [°]
% Landing Cycle
Left
Right

c)

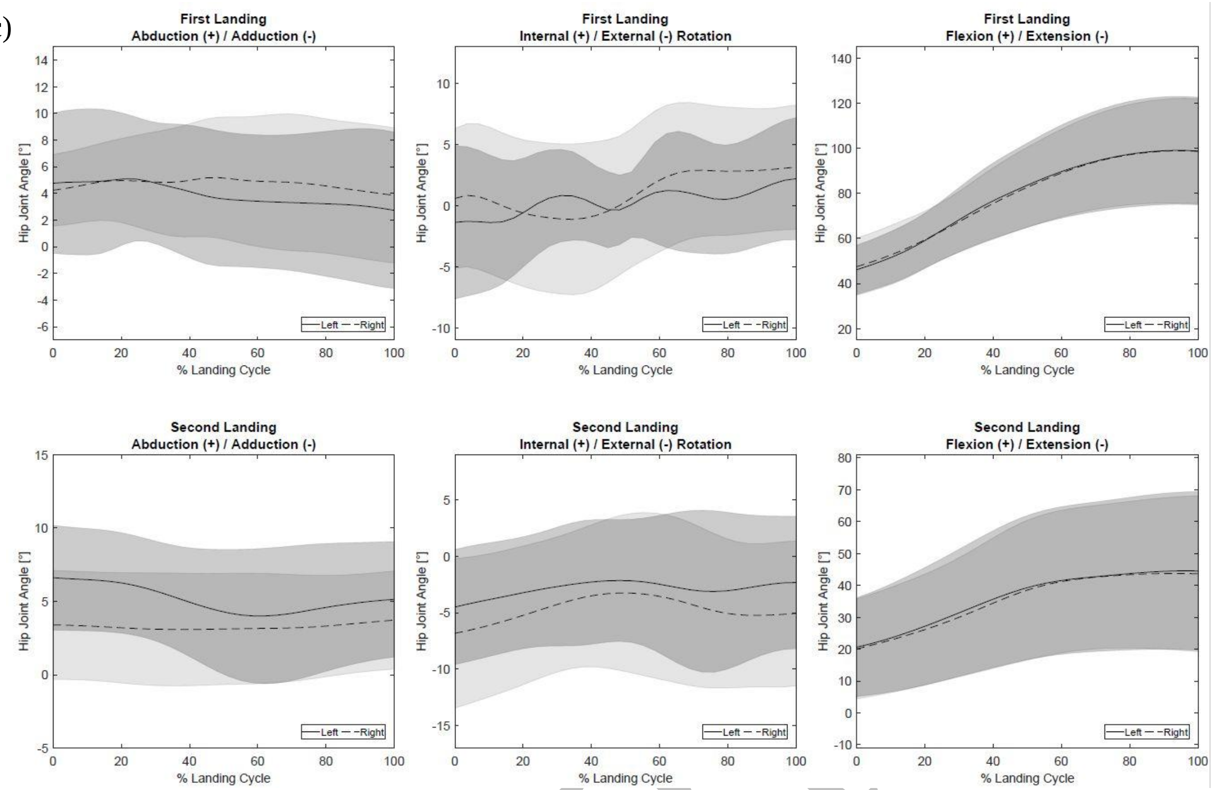


Figure 2. Means and standard deviations of (a) ankle, (b) knee and (c) hip joint patterns obtained from motion capture during first and second landings

3.2. Kinetic Results

The concentric mean power, jump height, peak landing force, peak power, and eccentric mean force parameters for the first landing were analyzed. Concentric mean power showed a strong positive correlation with eccentric mean force ($\rho = 0.648$, $p < 0.05$) and peak power ($\rho = 0.903$, $p < 0.01$). This suggests that participants with higher concentric mean power generally exhibited higher peak power.

Table 2: Kinetic Parameters of First DVJ

Participant	**Concentric Mean Power [W]**	**Jump Height [cm]**	**Peak Landing Force [N]**	**Peak Landing Force Asymmetry [% L, R]**	**Peak Power [W]**	**Eccentric Mean Force [N]**
P01	3831	27.1	3603	16,5L**	4720	1139
P02	3633	23	23	17,5L**	5176	1004
P03	5536	27.9	2027	18,8R**	8577	1902
P04	3833	29.5	5247	0,4L	6499	1085
P05	3518	31.9	3771	2,7R	4920	1048
P06	3325	19.2	2636	13,7R**	4341	1080
P07	2500	23.1	2243	0,1L	3787	802
P08	3839	23	4670	14,7R**	6056	869

P09	4107	31.5	4127	29,8L***	5659	1133
P10	2890	20.9	1960	6,8L*	4436	959
P11	3791	26.2	3461	13R**	5526	1118
P12	3657	25.4	3554	1,8L	5419	1020
Mean	***3709***	***25.8***	***3324***	***0.12L***	***5427***	***1104***
STD	***807***	***4.5***	***1148***	***14.3***	***1382***	***302***
****>25% Strong Asymmetry **25%-10% Moderate Asymmetry *10%-5% Mild Asymmetry <5% Negligible Asymmetry*						

Across all participants (n=12) the mean concentric power (3.7 kW ± 0.8), jump height (25.8 cm ±4.5), peak landing force (3324 N ±1148), peak landing force asymmetry (13% R), peak power (5.4 kW ± 1.3) and eccentric peak force (1104 N ± 302) parameters were calculated (Table 2). Individual athlete asymmetry scores were presented as vectors in Figure 3. Above 25% asymmetry between the right and the left limb loading percentages was considered strong asymmetry and observed in one participant. Asymmetry between 25%-10% was considered moderate and observed in 6 participants. One participant had mild asymmetry and only 4 participants had negligible asymmetry during landing on the force plate.

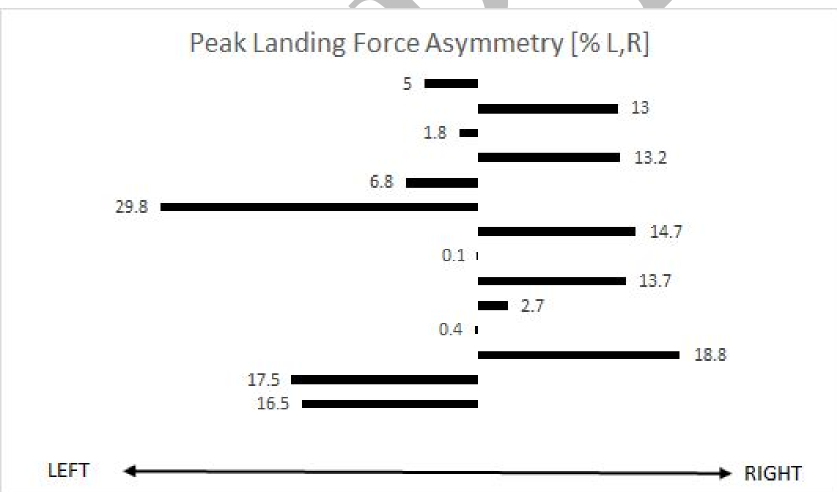


Figure 3. First landing force asymmetry scores for each participant represented as a percentage for peak force. (The left side of the plot indicates left side asymmetries, and the right side of the plot indicates right side asymmetries)

A highly significant positive correlation was found between the concentric mean power and the peak power ($\rho = 0.903$, $p < 0.01$). The mean concentric force and the mean eccentric force displayed a moderately positive and statistically significant relationship ($\rho = 0.648$, $p < 0.05$) (Table 3).

Table 3: Relationship between Kinetic Parameters of First DVJ

			Concentric Mean Power [W]	Jump Height (Flight Time) [cm]	Peak Landing Force [N]	Peak Power [W]	Eccentric Mean Force [N]
Spearman's rho	Concentric Mean Power [W]	Correlation Coefficient	1,000	,462	,455	,903**	,648*
		Sig. (2-tailed)	.	,179	,187	,000	,043
		N	12	12	12	12	12
	Jump Height [cm]	Correlation Coefficient	,462	1,000	,480	,468	,456
		Sig. (2-tailed)	,179	.	,160	,172	,185
		N	12	12	12	12	12
	Peak Landing Force [N]	Correlation Coefficient	,455	,480	1,000	,467	,103
		Sig. (2-tailed)	,187	,160	.	,174	,777
		N	12	12	12	12	12
	Peak Power [W]	Correlation Coefficient	,903**	,468	,467	1,000	,479
		Sig. (2-tailed)	,000	,172	,174	.	,162
		N	12	12	12	12	12
	Eccentric Mean Force [N]	Correlation Coefficient	,648*	,456	,103	,479	1,000
		Sig. (2-tailed)	,043	,185	,777	,162	.
		N	12	12	12	12	12

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

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4. Discussion

This study revealed significant asymmetries in the kinetic and kinematic parameters of elite female football players during the first landing phase of the DVJ. Notably, a pronounced asymmetry in knee internal/external rotation was observed during the initial landing, which improved in the second landing phase, indicating effective neuromuscular adaptation.

Recent studies examining DVJ biomechanics have strengthened its role as a predictive tool for identifying ACL injury risk, particularly in female athletes. The DVJ has become a cornerstone in both research and clinical settings due to its effectiveness in revealing high-risk kinematic and kinetic patterns, especially during the landing phase. Notably, female athletes frequently demonstrate increased dynamic knee valgus, reduced hip and knee flexion angles, and greater asymmetries in ground reaction forces—biomechanical characteristics commonly linked to non-contact ACL injuries. For instance, Sheikhi et al. (2024) highlighted that high-risk landing mechanics, such as excessive knee abduction moments and trunk instability, could be significantly mitigated through a comprehensive, systems-based injury prevention program, thereby reinforcing the DVJ's dual role as both a diagnostic and training instrument [25]. Sharir et al. (2024) further emphasized the sensitivity of the DVJ by showing that fatigue markedly worsens landing biomechanics during single-leg tasks in female athletes, accentuating the importance of evaluating athletes under fatigue conditions that reflect real-game scenarios [24]. Complementing this, Strong and Markström (2025) investigated the impact of secondary cognitive tasks on DVJ performance and observed that divided attention disrupted landing kinematics in athletes with a history of ACL reconstruction [27]. Their findings underscore the relevance of cognitive-motor interference in ACL risk assessment. A meta-analysis by Yoo (2024) demonstrated that neuromuscular training grounded in plyometric principles can meaningfully improve DVJ mechanics, including better joint control and shock absorption [31]. These results are especially pertinent considering the heightened risk for second ACL injuries in return-to-sport athletes. Weldon et al. (2024) recently found that altered DVJ performance can serve as a strong predictor of reinjury, even in athletes who have met standard return-to-play criteria [29]. Collectively, these investigations highlight the DVJ as more than a static biomechanical test; it is a dynamic, multifaceted assessment that can reveal critical deficits in neuromuscular control, proprioception, and motor planning—factors integral to ACL injury risk. Incorporating cognitive and fatigue-related challenges into DVJ protocols may offer a more ecologically valid and comprehensive evaluation of an athlete's injury risk, particularly in high-intensity sports such as football where decision-making under pressure is routine. These insights affirm the value of continually refining DVJ assessments as foundational elements in injury prevention strategies for female athletes.

The analysis of knee flexion angles between the first and second landing phases showed distinct differences. During the first landing, athletes landed with relatively stiff knees, contributing to greater reliance on the quadriceps for stabilization. In contrast, the second landing, involving a jump from the ground with an average height of 25.8 cm (SD = 4.5 cm), exhibited slightly more knee flexion, suggesting a more controlled landing posture. The reduced jump height in the second phase may have facilitated greater hamstring activation, potentially decreasing ACL strain. These differences emphasize the role of jump height and landing dynamics in knee flexion mechanics, which influence ACL stress. This highlights the importance of considering contextual factors in ACL injury prevention and the need for training strategies that address variations in landing conditions. Asymmetrical landing forces, where one leg absorbs more

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impact than the other, were found to increase the risk of ACL injury by placing uneven stress on the knee and impairing neuromuscular control [9], [24]. Our findings showed that asymmetry, particularly during high-impact landings, makes the non-dominant leg more vulnerable to ACL damage. This reinforces the need for targeted interventions to correct these asymmetries in training.

The relatively modest jump height values observed in this study may reflect limitations in lower-limb explosive strength among the tested group, despite their elite status. Jump height, particularly in the context of a DVJ, serves as an indirect but meaningful indicator of motor preparedness, as it relates to an athlete's ability to generate rapid force, a key requirement for dynamic football actions such as sprinting, cutting, and decelerating. These findings suggest that while the athletes demonstrated controlled landing mechanics, their capacity for vertical propulsion may be underdeveloped relative to optimal performance standards. This highlights a potential area for targeted neuromuscular training interventions focused on improving explosive strength. Enhancing vertical jump performance could contribute to more effective execution of sport-specific tasks and potentially reduce injury risk by improving the robustness of dynamic movement patterns in high-impact scenarios common in elite football.

Dynamic knee valgus, characterized by inward collapse of the knees during landing or cutting, contributes to ACL injuries by increasing medial-lateral shear forces. Female athletes are particularly prone to dynamic knee valgus due to structural factors like a wider pelvis, ligamentous laxity, and weaker hip abduction strength [16], [22]. In our study, significant asymmetry in knee internal/external rotation during the first landing phase was observed. Knee abduction angles at initial contact, along with peak knee abduction angles and moments, have been shown to correlate with a higher risk of non-contact ACL injuries. The rapid development of valgus and internal rotation within 40 milliseconds after initial contact is also associated with ACL injuries [8], [9], [30]. Our findings align with previous research showing that asymmetries in jump height and landing force distribution are predictive of factors associated with ACL injuries, such as altered joint loading and neuromuscular control deficits [8]. In addition, increased quadriceps dominance and delayed hamstring activation are known risk factors for ACL injuries [14]. Our results, which showed asymmetries in knee rotation and landing forces, support these findings. Notably, the absence of significant differences in these parameters during the second landing suggests that neuromuscular adaptation occurs after the first impact, leading to improved symmetry.

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Several studies have emphasized the importance of addressing force asymmetry during landings to reduce ACL injury risk [1]. Neuromuscular training programs focusing on hip abduction, external rotation, and hamstring strength have been shown to significantly reduce ACL injury risks in females [10], [26]. The neuromuscular adaptations observed in the second landing phase of our study could potentially be enhanced with strength training programs designed to reduce asymmetry and improve control during high-impact landings.

The study has the following limitations. First, the sample size, while representative of elite female football players, may limit the generalizability of our findings to broader populations, including athletes of varying skill levels, ages, or sports. Future studies with larger sample sizes would provide more robust statistical power and help validate these trends. Second, the study did not examine dynamic neuromuscular adaptations in subsequent movement phases, which would provide a more comprehensive understanding of biomechanical asymmetries and their injury risk implications. Additionally, while kinematic and kinetic asymmetries were identified, the study did not directly assess the effects of targeted interventions, such as strength training or neuromuscular control programs, on mitigating these imbalances or reducing ACL injury incidence. Longitudinal studies are needed to establish causal relationships. Lastly, the controlled laboratory setting of the study, while ensuring measurement accuracy, may not fully replicate the dynamic and unpredictable conditions of gameplay. Future research should aim to incorporate in-game assessments or wearable technology to bridge the gap between laboratory findings and real-world applications.

5. Conclusion

This study confirms that inter-limb biomechanical asymmetries, particularly in internal/external knee rotation and peak landing forces during the initial landing phase of a DVJ, are prevalent in elite female football players and may contribute to increased risk for ACL injury. The observation that these asymmetries diminish during the second landing phase suggests the presence of rapid neuromuscular adaptation mechanisms. However, the persistence of moderate-to-strong asymmetries in over half the sample highlights the need for targeted interventions.

From a practical standpoint, these findings underscore the importance of integrating DVJ assessments into athlete monitoring protocols to identify individuals at elevated risk. Corrective strategies should emphasize neuromuscular training that improves inter-limb

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symmetry, enhances hamstring activation, and promotes optimal joint control during landing tasks. Additionally, the relatively modest jump height values point to a need for enhanced explosive strength development, which may not only improve performance but also reduce injury susceptibility by promoting more robust movement patterns.

Future research should explore the longitudinal impact of individualized training programs designed to correct asymmetries and assess how these changes influence ACL injury rates. Expanding sample sizes and including real-game biomechanical monitoring will be essential to bridge laboratory findings with field relevance. Ultimately, these results support the use of interlimb biomechanical profiling as a practical and evidence-based approach to both performance enhancement and injury prevention in elite female football.

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