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Originals

Sagittal-plane lower-limb kinematics during single-leg landing in athletes: implications for knee injury risk

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ABSTRACT

Objective: To characterize sagittal-plane lower-limb kinematics during a standardized single-leg landing task and to compare landing mechanics between male and female athletes. **Methods:** One hundred and sixty-two athletes performed three single-leg landings from a 30-cm platform. Two-dimensional photogrammetric analysis was used to evaluate trunk, hip, knee and ankle kinematics at initial ground contact and at maximum knee flexion. Variables included knee flexion at initial contact and maximum knee flexion, hip flexion, trunk inclination, ankle position and ankle dorsiflexion range of motion. Independent t-tests were used to examine sex-related differences. **Results:** Athletes landed with a mean knee angle of $145.89 \pm 6.24^\circ$ at initial contact and reached a maximum knee flexion angle of $116.72 \pm 9.71^\circ$. Mean hip flexion increased from $10.02 \pm 1.82^\circ$ to $20.98 \pm 1.38^\circ$, while trunk position changed from $102.94 \pm 3.23^\circ$ at initial contact to $59.33 \pm 2.60^\circ$ at maximum knee flexion. Ankle dorsiflexion range of motion during landing was $41.54 \pm 4.32^\circ$. No significant differences were observed between males and females for any of the kinematic variables analysed ($p > 0.05$). **Conclusions:** Single-leg landing is characterized by coordinated sagittal-plane motion of the trunk, hip, knee and ankle. The absence of sex-related differences suggests that male and female athletes adopt similar landing strategies under standardized conditions. These findings support the use of an integrated biomechanical approach when assessing landing mechanics and may provide reference values for injury prevention, movement screening and rehabilitation programmes.

Keywords: Anterior cruciate ligament; Knee biomechanics; Motion analysis; Lower-limb kinematics; Landing.

Cinemática del miembro inferior en el plano sagital durante el aterrizaje unipodal en deportistas: implicaciones para el riesgo de lesión de rodilla

RESUMEN

Objetivo: Caracterizar la cinemática del miembro inferior en el plano sagital durante una tarea estandarizada de aterrizaje unipodal y comparar la mecánica de aterrizaje entre deportistas hombres y mujeres. **Métodos:** Ciento sesenta y dos deportistas realizaron tres aterrizajes unipodales desde una plataforma de 30 cm. Se utilizó un análisis fotogramétrico bidimensional para evaluar la cinemática del tronco, la cadera, la rodilla y el tobillo en el contacto inicial con el suelo y en la máxima flexión de rodilla. Las variables incluyeron la flexión de rodilla en el contacto inicial y en la máxima flexión de rodilla, la flexión de cadera, la inclinación del tronco, la posición del tobillo y el rango de movimiento de dorsiflexión del tobillo. Se utilizaron pruebas t independientes para examinar las diferencias relacionadas con el sexo. **Resultados:** Los deportistas aterrizaron con un ángulo medio de rodilla de $145,89 \pm 6,24^\circ$ en el contacto inicial y alcanzaron un ángulo máximo de flexión de rodilla de $116,72 \pm 9,71^\circ$. La flexión media de cadera aumentó de $10,02 \pm 1,82^\circ$ a $20,98 \pm 1,38^\circ$, mientras que la posición del tronco cambió de $102,94 \pm 3,23^\circ$ en el contacto inicial a $59,33 \pm 2,60^\circ$ en la máxima flexión de rodilla. El rango de movimiento de la dorsiflexión del tobillo durante el aterrizaje fue de $41,54 \pm 4,32^\circ$. No se observaron diferencias significativas entre hombres y mujeres para ninguna de las variables cinemáticas analizadas ($p > 0,05$). **Conclusiones:** El aterrizaje unipodal se caracteriza por un movimiento coordinado en el plano sagital del tronco, la cadera, la rodilla y el tobillo. La ausencia de diferencias relacionadas con el sexo sugiere que los deportistas hombres y mujeres adoptan estrategias de aterrizaje similares bajo condiciones estandarizadas. Estos hallazgos respaldan el uso de un enfoque biomecánico integrado al evaluar la mecánica del aterrizaje y pueden proporcionar valores de referencia para programas de prevención de lesiones, valoración funcional del movimiento y rehabilitación.

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Palabras clave: Ligamento cruzado anterior; Biomecánica de la rodilla; Análisis de movimiento; Cinemática del miembro inferior; Aterrizaje.

Cinemática dos membros inferiores no plano sagital durante a aterragem unipodal em atletas: implicações para o risco de lesão do joelho

RESUMO

Objetivo: Caracterizar a cinemática dos membros inferiores no plano sagital durante uma tarefa padronizada de aterragem unipodal e comparar a mecânica de aterragem entre atletas masculinos e femininos. **Métodos:** Cento e sessenta e dois atletas realizaram três aterragens unipodais a partir de uma plataforma de 30 cm. Foi utilizada a análise fotogramétrica bidimensional para avaliar a cinemática do tronco, quadril, joelho e tornozelo no contacto inicial com o solo e na flexão máxima do joelho. As variáveis incluíram a flexão do joelho no contacto inicial e na flexão máxima do joelho, a flexão do quadril, a inclinação do tronco, a posição do tornozelo e a amplitude de movimento de dorsiflexão do tornozelo. Foram utilizados testes t independentes para examinar as diferenças relacionadas com o sexo. **Resultados:** Os atletas aterraram com um ângulo médio do joelho de $145,89 \pm 6,24^\circ$ no contacto inicial e atingiram um ângulo máximo de flexão do joelho de $116,72 \pm 9,71^\circ$. A flexão média do quadril aumentou de $10,02 \pm 1,82^\circ$ para $20,98 \pm 1,38^\circ$, enquanto a posição do tronco mudou de $102,94 \pm 3,23^\circ$ no contacto inicial para $59,33 \pm 2,60^\circ$ na flexão máxima do joelho. A amplitude de movimento de dorsiflexão do tornozelo durante a aterragem foi de $41,54 \pm 4,32^\circ$. Não foram observadas diferenças significativas entre homens e mulheres para nenhuma das variáveis cinemáticas analisadas ($p > 0,05$). **Conclusões:** A aterragem unipodal caracteriza-se pelo movimento coordenado no plano sagital do tronco, quadril, joelho e tornozelo. A ausência de diferenças relacionadas com o sexo sugere que atletas masculinos e femininos adotam estratégias de aterragem semelhantes sob condições padronizadas. Estes achados apoiam a utilização de uma abordagem biomecânica integrada ao avaliar a mecânica de aterragem e podem fornecer valores de referência para programas de prevenção de lesões, triagem de movimento e reabilitação.

Palavras-chave: Ligamento cruzado anterior; Biomecânica do joelho; Análise de movimento; Cinemática dos membros inferiores; Aterragem.

INTRODUCTION

Landing is a fundamental component of many sporting actions, particularly those involving repetitive jumping, sprinting, and rapid changes of direction^{1,2}. From a biomechanical perspective, landing is a demanding motor task in which the lower extremity must rapidly dissipate impact forces while maintaining dynamic stability and preparing for subsequent movement^{3,4}. Efficient impact attenuation relies on the coordinated interaction of the trunk and lower-limb segments, allowing mechanical energy to be progressively absorbed through controlled joint motion rather than transferred to passive musculoskeletal structures^{1,5}. Consequently, landing has become one of the most widely used experimental tasks for investigating lower-limb biomechanics, as it provides a reproducible and functionally relevant model for evaluating movement strategies under conditions that closely resemble sporting performance^{6,3}. Altered landing mechanics have been associated with changes in impact absorption capacity, joint loading and neuromuscular control, highlighting the importance of understanding the kinematic characteristics that determine movement quality during this functional task^{7,2}.

Among the biomechanical determinants of landing performance, sagittal-plane kinematics play a fundamental role because they largely determine the capacity of the lower extremity to attenuate impact forces during the deceleration phase^{5,4}. In particular, knee flexion has been consistently recognised as one of the primary mechanisms responsible for shock absorption, facilitating eccentric muscle action and reducing the transmission of mechanical loads across the knee joint^{1,8}. However, the mechanical behaviour of the knee cannot be interpreted independently, since its motion is intrinsically linked to the coordinated contribution of adjacent segments^{1,5}. Hip flexion contributes to proximal control and regulates lower-limb alignment, trunk inclination influences the position of the centre of mass and external joint moments, while ankle motion, especially dorsiflexion during weight acceptance, facilitates the progressive transfer and dissipation of impact forces throughout the kinetic chain^{9,5}. Therefore, efficient landing mechanics should be

understood as the result of coordinated intersegmental motion rather than the isolated behaviour of a single joint, emphasising the need for comprehensive biomechanical analyses that simultaneously evaluate the kinematics of the trunk, hip, knee and ankle^{3,2}.

Previous investigations have demonstrated that modifications in sagittal-plane kinematics alter the mechanical demands experienced by the lower extremity during landing^{5,10}. Reduced knee flexion has been associated with stiffer landing strategies and diminished impact attenuation, while inadequate hip flexion, altered trunk positioning, and restricted ankle dorsiflexion may compromise load distribution across the lower limb^{5,11}. Nevertheless, recent evidence suggests that these variables should not be considered independent biomechanical factors but rather components of an integrated movement strategy in which the interaction between body segments determines overall landing performance^{1,4}. Consequently, analysing only a single joint may provide an incomplete representation of movement quality^{12,6}. A comprehensive evaluation including trunk, hip, knee and ankle kinematics at critical phases of landing, such as initial ground contact and maximum knee flexion, may therefore provide a more accurate characterisation of lower-limb movement patterns and improve our understanding of the biomechanical mechanisms underlying efficient impact absorption^{5,3}. Furthermore, these movement patterns have attracted considerable attention because they are considered relevant biomechanical mechanisms associated with non-contact anterior cruciate ligament injury, reinforcing the clinical relevance of studying landing kinematics within a functional and integrated framework^{1,7}.

Despite the growing body of research on landing biomechanics, several methodological limitations remain^{6,3}. Previous studies have predominantly focused on isolated biomechanical variables, kinetic measurements or injury prediction models, making direct comparisons difficult because of differences in landing protocols, participant characteristics and outcome measures^{6,2}. Moreover, although sagittal-plane kinematics are routinely assessed, relatively few investigations have simultaneously characterised trunk, hip, knee and ankle motion during the key phases of a standardized single-leg landing task¹². Assessing these segments at initial ground

contact and during impact absorption may provide a more comprehensive understanding of landing mechanics and identify movement strategies associated with effective impact attenuation^{13,10}. Furthermore, two-dimensional motion analysis provides a practical and clinically applicable approach to sagittal-plane assessment, with acceptable validity and reliability for several lower-limb kinematic variables^{14,3}.

Therefore, this study aimed to comprehensively characterise sagittal-plane kinematics during a standardized single-leg landing task by simultaneously assessing trunk, hip, knee, and ankle motion at initial ground contact and maximum knee flexion using two-dimensional photogrammetric analysis. It was hypothesised that landing would be characterised by coordinated, segment-specific kinematic patterns across these key phases, supporting a multisegmental approach to the assessment of landing mechanics.

Methods

Study design

This cross-sectional observational study aimed to characterize sagittal-plane lower-limb kinematics during a standardized single-leg

landing task using two-dimensional photogrammetric analysis. All experimental procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki and were approved by the Ethics Committee of the University of Sevilla. Prior to participation, all athletes received verbal and written information regarding the study procedures and potential risks before providing written informed consent.

Subjects

A total of 200 athletes were initially recruited to participate in this study. Following the eligibility screening, 38 volunteers withdrew before testing, resulting in a final sample of 162 participants. Participants were eligible if they engaged in physical activity for at least 30 minutes per day on three or more days per week and had not sustained any knee or ankle injury during the previous 12 months. Before testing, all participants completed a questionnaire regarding their weekly physical activity levels and provided anthropometric information, including age, height and body mass (Table 1).

Table 1. Anthropometric characteristics of the study participants.

Variables	Total	Men	Women
N	162	122	40
Age (years)	24 ± 3	25 ± 2	22 ± 1
Weight (N)	714.56 ± 125.18	754.59 ± 79.66	641.18 ± 44.34
Height (cm)	174 ± 7	180 ± 9	163 ± 6

Experimental procedure

Before testing, participants completed a standardized 5-minute warm-up followed by 15 familiarization trials to minimize potential learning effects. Each participant then performed three successful single-leg landings from a 30-cm platform, with one minute of recovery between trials. Participants were instructed to keep their hands on their iliac crests, gaze forward, and land naturally on their dominant limb, without specific instructions regarding landing technique. All trials were performed under identical experimental conditions.

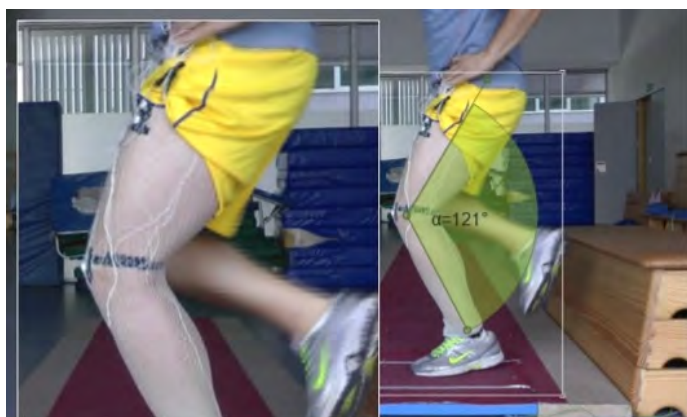


Figure 1. Experimental setup of the standardized single-leg landing task.

lower limb: the greater trochanter, the lateral femoral condyle, the lateral malleolus, and the midpoint of the ipsilateral shoulder. These landmarks were used to determine trunk, hip, knee and ankle joint angles throughout the landing task.

A digital video camera was positioned perpendicular to the sagittal plane at knee height, 2 m from the landing area to minimize perspective error. Joint kinematics were analysed at initial ground contact and maximum knee flexion, representing the onset and peak of the impact-absorption phase, respectively.

Sagittal-plane trunk, hip, knee, and ankle angles were assessed at both events, together with ankle dorsiflexion range of motion. Joint angles were defined according to standardized anatomical references: trunk angles were referenced to the ground (90° = upright, with lower values indicating greater forward flexion); hip angles to the horizontal plane (90° = horizontal thigh; 0° = vertically aligned femur); knee angles to full extension (180°, with lower values indicating greater flexion); and ankle angles ranged from 180° at maximum plantarflexion to 0° at maximum dorsiflexion. Angle definitions are illustrated in Figure 2.

Kinematic Assessment

Sagittal-plane lower-limb kinematics were assessed using two-dimensional photogrammetric analysis. Four reflective markers were placed on standardized anatomical landmarks of the dominant

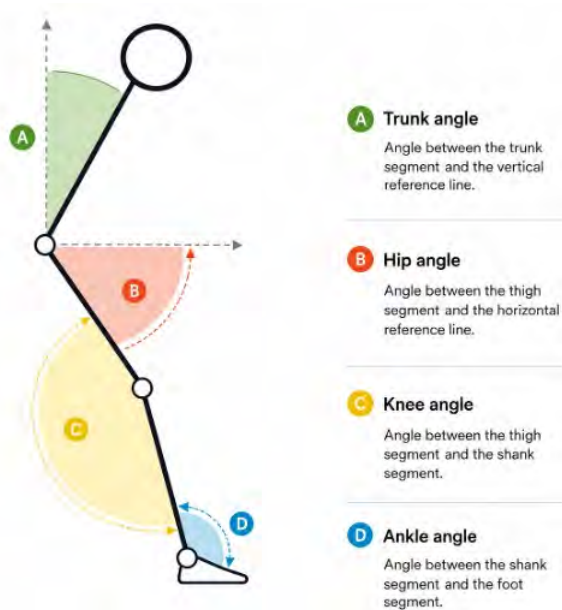


Figure 2. Definition of sagittal-plane joint angles obtained using two-dimensional photogrammetric analysis.

Statistical analysis

Table 2. Sagittal-plane kinematics during the single-leg landing task.

Variables	Mean $\pm$ SD
Initial knee flexion angle	145.89 $\pm$ 6.24
Maximum knee flexion angle	116.72 $\pm$ 9.71
Initial hip flexion angle	10.02 $\pm$ 1.82
Maximum hip flexion angle	20.98 $\pm$ 1.38
Initial trunk flexion angle	102.94 $\pm$ 3.23
Maximum trunk flexion angle	59.33 $\pm$ 2.60
Initial ankle angle	93.80 $\pm$ 2.61
Maximum ankle angle	52.26 $\pm$ 3.84
Ankle dorsiflexion ROM	41.54 $\pm$ 4.32

Data are presented as mean $\pm$ SD. All angular variables are expressed in degrees ($^{\circ}$). Initial angle refers to the first ground contact, whereas maximum angle corresponds to the instant of maximum knee flexion during landing. ROM = range of motion.

No statistically significant differences were observed between male and female athletes for any of the kinematic variables analysed during the landing task ($p > 0.05$; Table 3). Knee flexion at initial contact was $145.57 \pm 6.32^{\circ}$ in males and $147.13 \pm 5.87^{\circ}$ in females ($p = 0.184$), whereas maximum knee flexion reached $115.99 \pm 9.81^{\circ}$ and $118.83 \pm 9.15^{\circ}$, respectively ($p = 0.120$). Likewise, hip flexion,

Statistical analyses were performed using R statistical software (version 4.2.2; R Foundation for Statistical Computing, Vienna, Austria). Data normality was assessed using the Kolmogorov-Smirnov test, and descriptive statistics are presented as mean $\pm$ standard deviation (SD). Sex-related differences were analysed using independent-samples t-tests, while a two-way repeated-measures analysis of variance (ANOVA) was performed when appropriate to evaluate group and measurement-phase effects. Statistical significance was set at $p \leq 0.05$, with Bonferroni-adjusted p-values additionally calculated for multiple sex-related comparisons. Intraclass correlation coefficients (ICC) were calculated to assess the reliability of kinematic measurements. Effect sizes (Cohen's d) with corresponding confidence intervals were calculated to quantify the magnitude of observed differences.

Results

The sagittal-plane kinematic characteristics recorded during the standardized single-leg landing task are presented in Table 2. At initial ground contact, the mean knee flexion angle was $145.89 \pm 6.24^{\circ}$, decreasing to $116.72 \pm 9.71^{\circ}$ at maximum knee flexion during the impact absorption phase. Hip flexion increased from $10.02 \pm 1.82^{\circ}$ at initial contact to $20.98 \pm 1.38^{\circ}$ at maximum knee flexion. Similarly, trunk flexion changed from $102.94 \pm 3.23^{\circ}$ to $59.33 \pm 2.60^{\circ}$, while the ankle angle decreased from $93.80 \pm 2.61^{\circ}$ to $52.26 \pm 3.84^{\circ}$. The mean ankle dorsiflexion range of motion during landing was $41.54 \pm 4.32^{\circ}$.

trunk flexion, ankle angle, and ankle dorsiflexion range of motion did not differ significantly between male and female athletes (all $p > 0.05$). Cohen's d values indicated trivial to small effect sizes for all comparisons, supporting the absence of meaningful between-group differences. These findings remained unchanged after Bonferroni correction.

Table 3. Comparison of sagittal-plane kinematics between male and female athletes.

Variables	Men	Women	p-value	Cohen's d (95% CI)
Initial knee flexion angle	145.57 $\pm$ 6.32	147.13 $\pm$ 5.87	.184	0.251 (-0.05 - 0.552)
Maximum knee flexion angle	115.99 $\pm$ 9.81	118.83 $\pm$ 9.15	.120	0.294 (-0.007 - 0.595)
Initial hip flexion angle	10.14 $\pm$ 1.68	9.67 $\pm$ 2.22	.177	-0.257 (-0.558 - 0.043)
Maximum hip flexion angle	21.09 $\pm$ 1.29	20.67 $\pm$ 1.63	.111	-0.304 (-0.605 - -0.003)
Initial trunk flexion angle	102.93 $\pm$ 3.25	103.08 $\pm$ 3.20	.809	0.046 (-0.253 - 0.346)
Maximum trunk flexion angle	59.26 $\pm$ 2.68	59.59 $\pm$ 2.38	.498	0.126 (-0.174 - 0.426)
Initial ankle angle	93.62 $\pm$ 2.50	94.40 $\pm$ 2.91	.112	0.299 (-0.002 - 0.6)
Maximum ankle angle	51.95 $\pm$ 3.83	53.13 $\pm$ 3.80	.105	0.309 (0.008 - 0.61)

Variables	Men	Women	p-value	Cohen's d (95% CI)
Ankle dorsiflexion ROM	41.66 ± 4.30	41.27 ± 4.42	.630	-0.09 (-0.39 - 0.21)

Data are presented as mean ± SD. All angular variables are expressed in degrees (°). CI= confidence interval. Bonferroni-adjusted p-values are performed.

Discussion

The present study aimed to characterize sagittal-plane lower-limb kinematics during a standardized single-leg landing task and to determine whether sex-related differences exist in the movement strategy adopted by athletes. The main findings indicate that the landing task was characterized by a coordinated increase in knee and hip flexion together with ankle dorsiflexion during the impact absorption phase, while trunk motion remained within a range considered compatible with efficient load attenuation^{12,5,4}. Furthermore, no significant differences were observed between male and female athletes for any of the analysed kinematic variables^{15,16,11}. Collectively, these findings reinforce the concept that landing biomechanics should be interpreted as the result of coordinated intersegmental motion rather than the behaviour of an isolated joint, supporting current evidence that efficient impact attenuation depends on the interaction between the trunk, hip, knee and ankle throughout the landing manoeuvre^{17,12,1,18,3,7,4,2}.

Knee flexion has consistently been identified as one of the primary determinants of impact absorption during landing because it directly influences the distribution of mechanical loads across the lower extremity^{17,12,1,8,10}. In the present study, athletes landed with a mean knee flexion angle of approximately 34° at initial contact and progressively increased flexion to approximately 63° during the impact absorption phase. This movement pattern suggests that participants adopted an effective strategy to dissipate landing forces through progressive joint excursion rather than maintaining a relatively extended knee throughout ground contact^{13,11}. Previous biomechanical investigations have demonstrated that limited knee flexion during landing increases quadriceps dominance, anterior tibial shear forces and anterior cruciate ligament loading, whereas greater knee flexion facilitates mechanical energy dissipation and reduces the loads transmitted to passive joint structures^{1,5,19,20,10}. Although the present study did not quantify ligament loading directly, the observed kinematic profile appears consistent with a movement strategy that promotes impact attenuation through controlled sagittal-plane motion^{12,5}.

Our findings are generally consistent with previous investigations evaluating landing biomechanics under similar experimental conditions^{12,8,11}. Kristianslund and Krosshaug reported comparable knee flexion angles at initial contact during landing tasks, although participants in their study exhibited greater peak knee flexion than observed in the present investigation²¹. Differences in landing technique probably explain these discrepancies, as their protocol involved bilateral landings whereas the current study evaluated a single-leg landing task, which imposes greater stability demands and generally limits the available range of motion during impact absorption^{3,11}. Rather than considering these differences contradictory, they reinforce the notion that landing kinematics are highly task-dependent and should always be interpreted within the context of the specific motor demand being evaluated^{6,21,3}. Consequently, knee flexion should not be interpreted in isolation but as one component of an integrated neuromuscular strategy that continuously adapts to changes in task constraints^{12,4}.

However, contemporary evidence suggests that analysing knee motion alone provides only a partial understanding of landing biomechanics^{17,12,5}. During dynamic tasks, proximal segments substantially influence lower-limb alignment, and alterations in hip or trunk motion may modify knee loading despite similar sagittal-plane knee angles^{17,1,5,18,2}. This concept has gained increasing attention in recent years, shifting the focus from isolated joint

mechanics towards coordinated movement patterns involving the entire kinetic chain^{3,7,2}. Therefore, the interpretation of knee kinematics should always be accompanied by an evaluation of adjacent segments, particularly the hip and trunk, which play a fundamental role in controlling the position of the body's centre of mass throughout landing^{12,22,1,2}.

Consistent with this integrated perspective, the present study demonstrated a progressive increase in hip flexion throughout the landing manoeuvre^{12,4,23}. Athletes increased hip flexion from approximately 10° at initial contact to approximately 21° at maximum knee flexion, indicating active participation of the hip during impact absorption. Previous studies have similarly reported that greater hip flexion contributes to reducing knee loading by increasing the contribution of the hip extensors to energy absorption and improving control of lower-limb alignment^{24,3,25,26}. Likewise, van der Harst et al. described comparable hip flexion patterns during single-leg landing tasks, supporting the reproducibility of these movement characteristics across different populations²³. Although the magnitude of hip flexion observed in our study was slightly lower than previously reported, these differences are likely attributable to variations in landing protocols and participant characteristics rather than fundamentally different movement strategies^{6,23}.

The influence of trunk motion on landing biomechanics has also received increasing attention because trunk position directly affects whole-body balance and the mechanical demands imposed on the lower extremities^{1,5,2}. In the present study, trunk posture remained close to an upright position at initial contact before progressing towards greater flexion during the impact absorption phase^{12,5}. This behaviour agrees with previous investigations demonstrating that controlled forward trunk inclination facilitates hip recruitment, reduces knee extensor demand and contributes to a more favourable distribution of landing loads^{5,25}. Conversely, excessively upright trunk positions have been associated with increased knee extensor moments, greater anterior tibial loading and potentially less favourable landing mechanics^{8,27,28}. Importantly, trunk motion should not be interpreted as an isolated risk factor but rather as one element within the coordinated neuromuscular strategy that regulates lower-limb alignment during dynamic tasks^{1,3}.

The ankle also plays a fundamental role in landing biomechanics by regulating the transmission of forces from the foot to the proximal joints^{12,9,4}. In the present study, athletes exhibited a mean ankle dorsiflexion range of motion of approximately 41.5°, reflecting substantial sagittal-plane excursion during the impact absorption phase. Adequate dorsiflexion has been associated with a greater capacity to dissipate landing forces through progressive ankle motion, thereby reducing the mechanical demand transferred to the knee^{12,9,4}. Conversely, restricted ankle dorsiflexion has been linked to stiffer landing strategies, increased vertical ground reaction forces, reduced knee flexion and greater dynamic knee loading during high-impact tasks^{9,1,26}. Although the present investigation did not evaluate ankle mobility as an isolated predictor of injury, the dorsiflexion values observed suggest that participants adopted an ankle strategy compatible with effective impact attenuation during landing^{12,4}.

Taken together, the findings of the present study reinforce the concept that landing biomechanics should not be interpreted through isolated joint behaviour^{12,3,4}. Instead, efficient impact absorption emerges from the coordinated interaction between the trunk, hip, knee and ankle, each contributing to the progressive dissipation of mechanical energy throughout the landing manoeuvre^{12,5,2}. Recent biomechanical research increasingly supports this systems-based perspective, demonstrating that alterations in one segment inevitably

influence movement patterns in adjacent joints^{1,5,3}. Consequently, focusing exclusively on knee flexion provides an incomplete representation of landing mechanics and may oversimplify the mechanisms underlying both performance and injury risk^{3,7,2}. From this perspective, the kinematic profile observed in the present study appears to represent an integrated movement strategy in which coordinated sagittal-plane motion across multiple segments facilitates efficient load distribution while maintaining dynamic stability during landing.

Contrary to the commonly reported higher incidence of knee injuries in female athletes, no statistically significant sex-related differences were identified in any of the analysed kinematic variables^{16,4,11}. These findings suggest that, under standardized landing conditions, male and female athletes adopted remarkably similar sagittal-plane movement strategies^{16,4}. Previous investigations have frequently described females as landing with reduced knee and hip flexion and a more upright trunk posture, characteristics that have traditionally been associated with increased anterior cruciate ligament loading^{8,27,10}. However, more recent evidence indicates that sex alone does not consistently explain biomechanical variability and that individual neuromuscular control, physical capacity, task characteristics and training background may exert a greater influence on landing mechanics than biological sex itself^{9,7}. Therefore, the absence of sex differences observed in the present study supports the growing consensus that movement quality should be evaluated individually rather than assuming stereotypical biomechanical patterns based exclusively on sex^{3,7}.

These findings have several practical implications for clinicians, strength and conditioning coaches, and rehabilitation professionals^{1,6,2}. Since landing biomechanics depend on coordinated intersegmental motion rather than isolated knee behaviour, assessment protocols should incorporate the simultaneous evaluation of trunk, hip, knee and ankle kinematics^{12,18,3,2}. Likewise, neuromuscular training programmes designed to optimise landing technique should prioritise movement quality and whole-body coordination instead of focusing exclusively on increasing knee flexion^{1,5,3,2}. This integrated approach may improve impact absorption efficiency, optimise lower-limb mechanics and potentially contribute to reducing excessive mechanical loading during sport-specific tasks^{1,13,2}. Although the present study was not designed to establish causal relationships with injury occurrence, the kinematic profile described here may provide useful reference values for functional assessment, movement screening and return-to-sport decision-making following lower-limb injuries^{1,3,7}.

Overall, the present findings demonstrate that single-leg landing is characterised by a coordinated sagittal-plane movement strategy involving the trunk, hip, knee and ankle^{12,5}. Rather than identifying isolated joint positions associated with injury risk, the results support the concept that effective landing performance depends on the integration of multiple segments acting together to attenuate impact forces^{12,3,4}. Consequently, the evaluation of landing biomechanics should adopt a comprehensive approach that considers the interaction between lower-limb joints and the trunk, providing a more complete understanding of movement quality and its potential implications for injury prevention and athletic performance^{12,1,6,2}.

Limitations

Despite the strengths of the present study, several limitations should be acknowledged. First, joint kinematics were assessed using two-dimensional photogrammetric analysis, which only allows the evaluation of movement in the sagittal plane and does not capture three-dimensional joint mechanics, particularly frontal and transverse plane motions that may also contribute to knee injury mechanisms. Second, kinetic variables, including ground reaction forces and joint moments, were not recorded, preventing a comprehensive interpretation of the mechanical demands experienced during landing. Third, muscle activation patterns were

not evaluated, making it impossible to determine the neuromuscular strategies underlying the observed kinematic behaviour. Finally, although the sample included a large number of athletes, participants were not stratified according to sport discipline or competitive level, factors that may influence landing mechanics. Future studies should integrate three-dimensional motion analysis, kinetic assessments and electromyographic measurements to provide a more comprehensive understanding of lower-limb biomechanics during landing tasks.

Conclusions

The present study provides a comprehensive characterization of sagittal-plane lower-limb kinematics during a standardized single-leg landing task in athletes. The findings demonstrate that landing performance is characterized by coordinated motion of the trunk, hip, knee and ankle, supporting the concept that impact attenuation depends on the integrated contribution of multiple segments rather than the behaviour of an isolated joint. Furthermore, no significant sex-related differences were identified under the standardized testing conditions employed in this study. These findings reinforce the importance of adopting a whole-body biomechanical approach when evaluating landing mechanics and may provide useful reference values for movement assessment, injury prevention strategies and rehabilitation programmes aimed at optimizing lower-limb function.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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