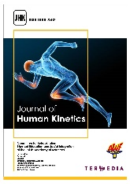

Sex Differences in Force-Time Curve Characteristics during Single-Leg Drop Jumps with Increased Drop Heights

by

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This study examined sex differences in force-time curve metrics during single-leg drop jumps (SLDJs) from 20-cm and 30-cm drop heights. Forty participants (26 males, 14 females) performed SLDJs, assessing jump height, the reactive strength index (RSI), and force-time curve characteristics. The force-time curve was categorized as poor (presence of an impact peak and a non-spring-like), moderate (impact peak with a spring-like), or good (no impact peak with a spring-like). While jump height and the RSI were unaffected, peak force ($\eta^2_p = 0.202$, $p < 0.001$) and its timing ($\eta^2_p = 0.184$, $p < 0.001$) increased with height. Only females exhibited reduced spring-like correlation at 30 cm ($\eta^2_p = 0.200$, $p < 0.001$) and greater force reduction from peak force to the lowest center of mass displacement ($\eta^2_p = 0.052$, $p < 0.001$). At 30 cm, 14.3% of females had a poor force-time curve, compared to 0% of males. Females exhibited distinct biomechanical responses to higher drop heights, highlighting the need for sex-specific injury prevention strategies.

Keywords: *vertical ground reaction force; anterior cruciate ligament injuries; sex factors; single-leg drop jump; force-time curve*

Introduction

Anterior cruciate ligament (ACL) injuries are among the most common and severe sports-related injuries, often requiring surgical reconstruction and have prolonged rehabilitation periods lasting 6 to 13 months (Lai et al., 2018). Despite advancements in surgical techniques and rehabilitation protocols, only 60% of non-elite athletes and 79% of elite athletes successfully return to their pre-injury performance levels after ACL injuries (Ardern et al., 2014). These injuries pose significant challenges to athletes' physical and psychological well-being and lead to long-term functional impairment and an increased risk of re-injury (Manojlovic et al., 2024).

ACL injuries frequently occur during single-leg, high-intensity deceleration movements, such as cutting, pivoting, or landing (Koga et al., 2010). These injuries are predominantly non-contact in nature, with the ground reaction force (GRF) during landing identified as a critical external factor contributing to peak ACL strain (Boden and Sheehan, 2022). Notably, females experience ACL injuries at a rate 1.4 to 4.1 times higher than males (Chia et al., 2022; Gornitzky et al., 2016), a disparity attributed to anatomical (Pradhan et al., 2023), hormonal (Berger et al., 2023), and biomechanical differences (Ellison et al., 2021). However, current screening and prevention strategies often fail to account for sex-specific biomechanical variations, highlighting the need for more targeted approaches (Smith et al., 2012). Additionally, because ACL injuries typically occur in the early phase after initial ground contact (Koga et al., 2010), evaluating GRF characteristics during the early stance phase, particularly the braking phase, is crucial for identifying risk factors.

The drop vertical jump (DVJ) is widely used to assess the ACL injury risk by simulating movements that replicate sports-related injury scenarios (Hewett et al., 2005; Leppänen et al., 2017; Smith et al., 2012). This test evaluates the stretch-

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shortening cycle (SSC), which is essential for effective energy transfer during the rapid braking and propulsion phases (Pedley et al., 2023). However, the use of the DVJ to predict injury risk remains controversial**.** One reason may be that predictive variables are often limited to peak values (Krosshaug et al., 2016). Recent studies have emphasized the importance of analyzing the entire force-time curve to gain a more comprehensive understanding of SSC function and landing mechanics in the DVJ (Maestroni et al., 2023; Pedley et al., 2021, 2025; Read et al., 2022; Wang et al., 2025). Another factor may be the standardized use of drop heights regardless of sex. This approach may fail to account for key sex differences, such as height, strength, and joint stiffness, potentially leading to disproportionate mechanical demands on females. Studies have demonstrated that males generally exhibit greater leg and ankle joint stiffness during single-leg drop landings than females (Ward et al., 2019). Moreover, research indicates that as the drop height increases, females experience significant biomechanical changes, including increased GRF, joint moments, and power (Dickin et al., 2015). These sex-related biomechanical differences may stem from physiological factors such as disparities in muscle strength (Brophy et al., 2009), neuromuscular control (Hu et al., 2023; Lee et al., 2015), and increased joint laxity (Park et al., 2009) influenced by sex hormones. Consequently, when performing the task at the same drop height, both males and females may perceive its difficulty differently, potentially masking underlying sex differences in biomechanical responses.

This study aimed to address these gaps by analyzing sex-specific biomechanical characteristics during single-leg drop jumps (SLDJs) at varying drop heights. By focusing on detailed force-time curve metrics, particularly during the braking phase, along with GRF patterns, this study sought to identify sex-specific adaptations in jump strategies. We hypothesized that increasing drop heights would lead to significant alterations in shock absorption and SSC efficiency in females compared to males, providing insights for the development of tailored injury prevention strategies.

Methods

Participants

Based on previous data evaluating the interaction effect size between tasks related to sex-differences in peak GRF (Peebles et al., 2020), a priori power analysis using G*Power software (version 3.1.9.6, Düsseldorf, Germany) revealed that a total sample size of 28 was required to achieve a power of 0.9, with an input effect size of 0.33 at $\alpha = 0.05$.

A total of 40 team-sport athletes participated in this study, including 26 males (age: 24.0 ± 4.2 years, body mass: 72.6 ± 8.5 kg, body height: 1.70 ± 0.04 m; 24 soccer players, 2 ultimate frisbee players) and 14 females (age: 21.8 ± 2.9 years, body mass: 57.9 ± 9.5 kg, body height: 1.64 ± 0.03 m; 11 soccer players, 2 ultimate frisbee players, 1 basketball player). All participants were members of university sports clubs or elite club teams and trained in their respective sports at least four days per week. In addition to their sport-specific training, both male and female participants regularly engaged in resistance and plyometric training at least once per week as part of their structured conditioning routines to enhance athletic performance. Exclusion criteria included a history of lower extremity surgery within the past 6 months or any condition that could interfere with single-leg drop jump performance. This study was approved by the Institutional Review Board of the Waseda University, Saitama, Japan (protocol code: 2023-165; approval date: 20 July 2023) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants.

Measures

Design and Procedures

Participants began with a warm-up consisting of 5 minutes of running at a comfortable pace, followed by four dynamic stretches targeting the hamstrings, gluteus, rectus femoris, and gastrocnemius muscles. Practice trials were conducted to familiarize the participants with the single-leg drop jump (SLDJ), after which SLDJ measurements were performed.

Single-Leg Drop Jump

The trial only assessed the participants' dominant leg, which was defined as the leg they preferred for kicking a ball. Participants performed the trials barefoot to ensure consistent force plate measurements. The SLDJ was executed from steps of 20 cm and 30 cm. The force plate was positioned 12 cm forward from the step edge (Pedley et al., 2023). To prevent participants from stepping down or jumping up, each trial began from a single-leg stance with the non-jumping leg flexed at approximately 60 degrees at the knee. The stance leg was kept fully extended at the knee and hip joints (Figure 1). These instructions were applied consistently across both drop heights. Participants were instructed to drop from the step and, upon landing on the force plate, immediately jump as high as possible while minimizing ground contact time. Both landing and take-off occurred on the same leg, and participants remained stationary for 3 s after landing. Participants kept their hands on their hips throughout the trial. If a participant failed to remain stationary for 3 s after landing or removed their hands from their hips at any point during the movement, the trial was repeated. Three successful trials were recorded, and the trial with the highest reactive strength index (RSI) was selected for reporting and subsequent force-time analysis (Figure 1).

Data Processing

The SLDJ trials were performed on a force plate (9287CA, Kistler Japan Inc., Kanagawa, Japan) and analyses were conducted using MATLAB version 9.14 software (R2023a; MathWorks, Natick, MA). Vertical ground reaction force (vGRF) data were recorded at a sampling rate of 1,000 Hz and smoothed using a fourth-order recursive low-pass Butterworth filter with a 30-Hz cutoff frequency. A summary of calculation methods for each variable included in this study is provided in Table 1.

The movement was divided into phases. Initial contact (IC) was identified as the point at which the vGRF first exceeded 15 N, while take-off was defined as the point where the vGRF subsequently dropped below 15 N. The interval between IC and take-off was designated as the first contact phase. Following takeoff, the point where the vGRF exceeded 15 N was identified as the second contact, and the interval between takeoff and the second contact was classified as the flight phase. The period following the second contact was defined as the second-contact phase, during which participants remained stationary for 3 s. The velocity was set to zero at a specific point and determined using a moving average method to calculate the coefficient of variation (CV) of vGRF over 300-ms intervals.

The point at which the CV dropped below 1% was identified as the most stable moment and was used as the reference for setting the velocity to zero (Yamashita et al., 2020). Using this reference point, acceleration was calculated by dividing the GRF by body mass, and velocity was obtained from the stable point to take-off using backward numerical integration with the trapezoid rule (McMahon et al., 2021). Jump height was also calculated from the take-off velocity, and displacement-time data were then derived by performing a second numerical integration of the velocity-time data. The braking phase was defined as the period from IC to the point when the center of mass (CoM) velocity crossed zero. The propulsion phase was defined as the period from the lowest CoM displacement to takeoff. To characterize the braking phase, specific variables were calculated, including the proportion of the braking phase length relative to the first contact phase and the reduction in force from the peak force to the force at the lowest CoM displacement. GRF data were normalized to body mass (BM) and resampled to 101 data points for standardized comparisons. Classification of GRF profiles followed two criteria based on previous research: (1) the presence of an impact peak, defined as a transient and visible force peak occurring within the first 20% of the first contact phase (Pedley et al., 2023), and (2) spring-like behavior, defined as a Pearson product-moment correlation coefficient of less than −0.80 between vertical GRF and vertical CoM displacement throughout the entire contact phase (Padua et al., 2005).

Previous research has demonstrated that simple spring-mass models suggest a sinusoidal relationship between vGRF and CoM displacement during ground contact, with the two effectively mirroring each other (Blickhan, 1989). Based on this, ideal spring-like behavior is defined as a state characterized by a strong negative correlation between vertical GRF and COM displacement. A scientific basis for using a correlation coefficient of less than −0.80 as a criterion for identifying spring-like behavior has also been established (Padua et al., 2005). Building

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on this foundation, this study adopted the same threshold as the standard. Participants were categorized as good (no impact peak and spring-like behavior), moderate (either an impact peak with spring-like behavior, or no impact peak with non-spring-like behavior), or poor (impact peak present and non-spring-like behavior) (Pedley et al., 2023) (Figure 2).

Statistical Analysis

Statistical analyses were conducted using R (Version 4.4.2 R Foundation for Statistical Computing, Vienna, Austria) with an α level of 0.05. Normally distributed variables were reported as mean ± standard deviation (SD), whereas non-normally distributed variables were reported as mean ± SD and median with interquartile range (IQR). The Shapiro-Wilk test was used to assess data normality. For normally distributed variables, a two-way analysis of variance (ANOVA) was conducted, with sex (male or female) as a between-subjects factor and drop height (20 cm or 30 cm) as a within-subjects factor. The interaction between sex and drop height was also analyzed to determine its effect on biomechanical sex differences. When a significant interaction was found, Bonferroni post hoc procedures were performed. For non-normally distributed variables, including spring-like correlations and vGRF-RoD (%), an aligned rank transform was applied based on a previous study (Elkin et al., 2021). Post hoc testing for these variables was conducted using the Tukey's test. Effect sizes were evaluated using partial eta-squared (η^2_p) to assess the magnitude of significant differences. The experimental effect was classified as small for $0.01 \le \eta^2_p < 0.06$, medium for $0.06 \le \eta^2_p < 0.14$, and large for $\eta^2_p \ge 0.14$. Additionally, for variables subjected to post hoc tests, Cohen's d with 95% confidence intervals (CIs) was calculated and interpreted based on the following criteria: 0.20 < small ≤ 0.50 < medium ≤ 0.80 < large (Cohen, 1988).

Chi-squared (χ^2) analyses were performed to investigate GRF category agreement across sexes and drop heights. In the chi-squared test, adjusted standardized residuals were analyzed to identify frequencies that deviated significantly from the whole group distribution by more than ±1.96 z-scores ($p \le 0.05$). Adjusted residuals were converted into chi-squared values, and then corresponding p-values.

Results

Table 2 presents the data for the SLDJ variables. The two-way ANOVA revealed a significant main effect of sex on both jump height ($\eta^2_p = 0.302$, $p < 0.001$) and the RSI ($\eta^2_p = 0.431$, $p < 0.001$), whereas no interaction or other effects were observed for these variables. For peak force values, a significant main effect of drop height was observed ($\eta^2_p = 0.202$, $p < 0.001$), with no interaction effects. Regarding peak force timing, significant main effects of both drop height and sex were observed （$\eta^2_p = 0.184$, $p < 0.001$, $\eta^2_p = 0.078$, $p < 0.01$), but no interaction effects were found. In contrast, for spring-like correlation, a significant interaction effect was observed ($\eta^2_p = 0.200$, $p < 0.001$), with no significant main effects of drop height or sex detected. Results showed that, for females, the spring-like correlation significantly decreased from 20 cm to 30 cm (Cohen's $d = 1.73$, 95% CI [0.81, 2.65]; $p < 0.001$). At 30 cm, females demonstrated significantly lower values compared with males (Cohen's $d = -1.8$, 95% CI [−2.6, −1.0]; $p < 0.001$). No significant interactions or main effects were observed for the braking phase duration (%). For peak force, no interaction effects were found; however, a significant main effect of drop height was observed. Regarding vGRF-RoD (%), significant interaction effects ($\eta^2_p = 0.052$, $p < 0.001$) and main effects of drop height ($\eta^2_p = 0.258$, $p < 0.001$) were identified. Post hoc analysis revealed the following comparisons: for males, vGRF-RoD (%) significantly decreased from 20 cm to 30 cm (Cohen's $d = -0.96$, 95% CI [−1.55, −0.37]); for females, the vGRF-RoD (%) significantly decreased from 20 cm to 30 cm (Cohen's $d = -2.25$, 95% CI [−3.25, −1.24]). Additionally, at 30 cm, females demonstrated a significantly greater vGRF-RoD (%) compared to males (Cohen's $d = 1.70$, 95% CI [0.92, 2.47]).

The distribution of the SSC function categories (good, moderate, and poor) was analyzed based on jump height and sex (Figure 3). Among females performing a 20-cm jump, 64.3% were categorized as good, 35.7% as moderate, and none as poor. At 30 cm, 35.7%, 50%, and 14.3% of participants were classified as good, moderate, and poor, respectively. Among males performing a 20-cm jump, 65.4% were categorized as good, 34.6% as moderate, and none as poor. At 30 cm, 50% of the participants were categorized as good, 50% as moderate, and none as poor. Because some categories contained zero values, chi-squared analysis could not be performed. Notably, the proportion of trials categorized as poor increased only for females at 30 cm, whereas no poor cases were observed for males at 30 cm.

Table 1. Description of the variables examined.

Variables	Description
Jump Height (m)	Calculated from take-off velocity using the backward integration method: $V_{take\text{-}off}^2/(2g)$, where g = 9.806 m/s.
RSI (m/s)	Jump height divided by first contact phase length.
Peak Force (BM)	Highest transient, visible force peak during the landing phase.
Peak Force Timing (%)	Time taken to achieve force peak during the landing phase.
Spring-like correlation	Pearson product-moment correlation between GRF and CoM displacement.
Braking phase duration (%)	The percentage of contact time from ground contact to the point when the CoM velocity crosses zero.
vGRF-RoD (%)	Percentage decrease in GRF from peak force to force at lowest CoM displacement.

Table 2. Results of two-way ANOVA for each variable.

		Mean ± SD		Median (IQR)		Interaction	Main effect: Gender	Main effect: Height
		20 cm	30 cm	20 cm	30 cm	*p* value Partial η2	*p* value Partial η2	*p* value Partial η2
Jump Height (m)	Female	0.09 ± 0.03[a]	0.10 ± 0.03[a]			-	$p < 0.001$ 0.302 (Large)	-
	Male	0.18 ± 0.04	0.17 ± 0.04					
RSI (m/s)	Female	0.32 ± 0.14[a]	0.34 ± 0.15[a]			-	$p < 0.001$ 0.431 (Large)	-
	Male	0.59 ± 0.13	0.56 ± 0.14					
Peak Force (%BW)	Female	3.38 ± 0.51	4.16 ± 0.55[b]			-	-	$p < 0.001$ 0.202 (Large)
	Male	3.54 ± 0.42	3.90 ± 0.49[b]					
Peak Force timing (%)	Female	25.4 ± 5.8	19.8 ± 2.7[a,b]			-	$p < 0.01$ 0.078 (Medium)	$p < 0.001$ 0.184 (Large)
	Male	35.0 ± 14.0	23.3 ± 8.3[b]					
Spring-like correlation	Female	0.95 ± 0.03	0.86 ± 0.06[a,b]	0.96 (0.93–0.97)	0.87 (0.84–0.90)	$p < 0.001$ 0.200 (Large)	-	-
	Male	0.91 ± 0.08	0.94 ± 0.03	0.94 (0.90–0.96)	0.94 (0.92–0.96)			
Braking phase duration (%)	Female	45.1 ± 2.1	42.9 ± 5.9			-	-	-
	Male	44.5 ± 4.3	44.7 ± 2.4					
vGRF-RoD (%)	Female	11.3 ± 6.9	29.0 ± 8.8[a,b]	9.2 (8.2–12.1)	30.6 (20.7–34.9)	$p < 0.001$ 0.052 (Small)	-	$p < 0.001$ 0.258 (Large)
	Male	6.3 ± 6.0	13.7 ± 9.1[b]	4.7 (1.2–19.4)	12.7 (7.2–19.0)			

Data are presented as mean ± SD; for nonparametric variables, values are expressed as medians [IQR]. Post hoc tests were performed for variables with significant interactions. For significant interactions and main effects of sex or drop height ($p < 0.05$), p-values and partial η^2 are reported; a: significant difference compared with males of the same height; b: significant difference between jump heights of the same sex

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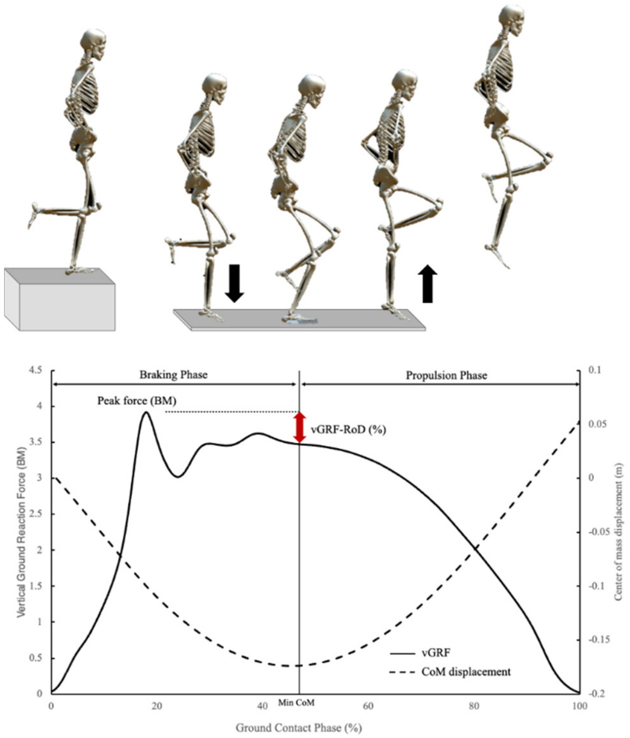

Figure 1. Examples of force-time curves and center of mass (CoM) displacement curves for single-leg drop jumps (SLDJs).

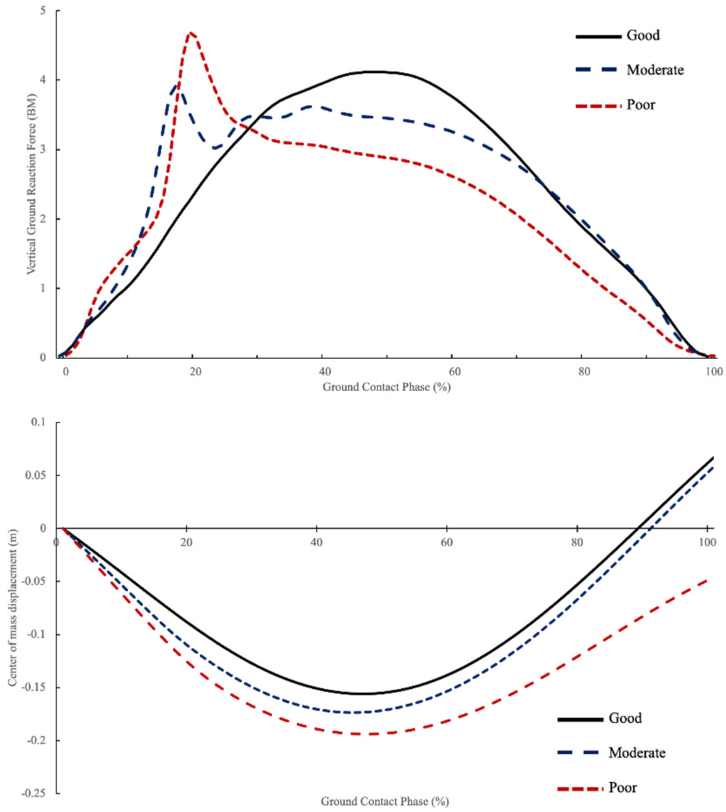

Figure 2. Vertical ground reaction force (vGRF) time curve and center of mass (CoM) displacement, categorized as good, moderate, and poor.

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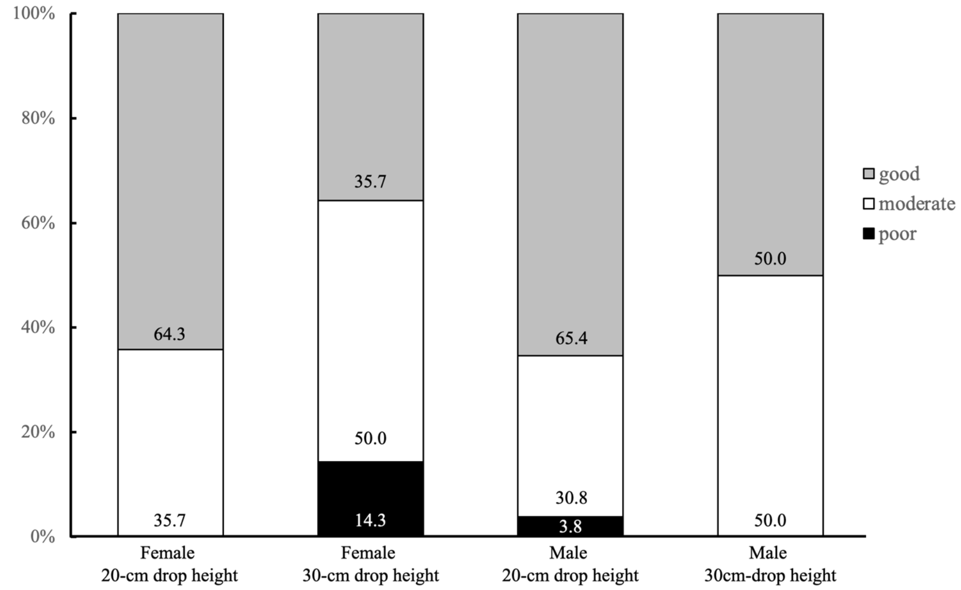

Figure 3. Distribution of stretch-shortening cycle (SSC) categories—good, moderate, and poor—for males and females at 20-cm and 30-cm drop heights.

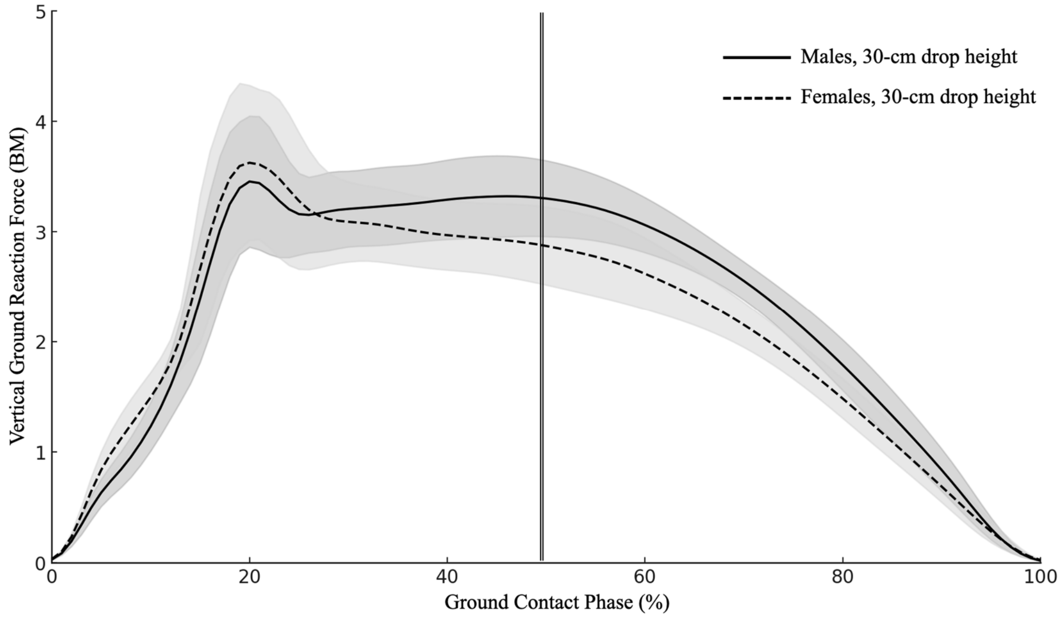

Figure 4. Force-time curves for a 30-cm single-leg drop jump, presented as mean ± standard deviation (SD). The solid line represents male data, and the dashed line represents female data. The shaded areas indicate ±1 SD around the mean for each group.

Discussion

This study examined the impact of increased drop height on force-time curve metrics during SLDJs, revealing key sex-specific differences. Although jump height and the RSI remained unaffected by drop height in both sexes, increased drop height significantly influenced peak force value and timing. Notably, only female participants demonstrated a marked decline in spring-like correlation and a greater reduction in force at the lowest CoM displacement. These findings suggest that females might rely on less effective shock absorption strategies when needing to decelerate rapidly from greater velocities. As illustrated in Figure 4, notable differences in the braking phase were observed at a drop height of 30 cm, highlighting the impact of drop height on sex-specific adaptations during landing.

As indicated by the results of this study, only females exhibited a decline in the spring-like correlation with increased drop height. Despite no significant sex differences in the peak force value, females demonstrated a greater reduction in GRF from peak to minimum CoM displacement than males. These findings highlight the sex-specific differences in shock absorption. Romanchuk et al. (2020) reported that during the braking phase of the SLDJ, from drop heights adjusted by the tibial length, females relied more heavily on ankle joint contributions and less on hip joint contributions compared to males. Additionally, Wang and Peng (2014) demonstrated that when the drop height increased from 20 to 30 cm in male participants, the impact peak increased, which is consistent with the current findings; however, ankle stiffness and peak power remained unchanged. Based on these findings, it is plausible that females may be less effective at absorbing larger impact forces during landing. This reduced efficiency could be attributed to the biomechanical reliance on distal joints such as the ankle rather than proximal joints such as the hip, which may limit their ability to manage higher impact forces effectively.

Another notable finding was that increasing drop height did not affect jump height or the RSI, which are commonly used performance indicators. However, these metrics may not fully reflect biomechanical adaptations to changes in drop height. Previous studies have shown that examining GRF characteristics during the braking phase of SLDJs in patients after ACL reconstruction can identify differences which are not detected by the RSI or jump height (Read et al., 2022). ACL injuries often occur during rapid single-leg deceleration movements, typically early in ground contact (Koga et al., 2010). Therefore, analyzing GRF characteristics during the braking phase of the SLDJ, as demonstrated in this study, provides valuable insights.

This study has several limitations that should be acknowledged. First, the sample size, particularly the imbalance between male and female participants, may have limited the generalizability of the findings. Future studies with larger and more balanced sample sizes are required to confirm these findings. Secondly, this study exclusively targeted recreationally active college-aged individuals, which may not reflect the biomechanical characteristics of elite athletes or younger populations. To enhance applicability, establishing normative thresholds for different age groups, skill levels, and competition levels is essential. Third, although force-time curve metrics provide valuable insights, incorporating kinematic data or muscle activation patterns through electromyography (EMG) could further elucidate the mechanisms underlying the observed sex differences. Finally, although the difference between the 20-cm and 30-cm conditions was consistently maintained, the actual drop heights may have been lower than the nominal platform heights, despite strict standardization of the starting posture. Further refinement of methods for controlling and verifying drop height will be necessary in future studies.

Future research should focus on longitudinal studies to evaluate the predictive validity of single-leg drop jumps for ACL injury risk in diverse populations. Furthermore, exploring the interaction among drop height, joint mechanics, and neuromuscular control within sports-specific scenarios requiring greater impact absorption could provide deeper insights into injury mechanisms. Developing and validating sex-specific training protocols, informed by detailed biomechanical analyses like those presented in this study, will be crucial for advancing ACL injury prevention and rehabilitation practices.

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Conclusions

This study revealed that increasing drop height influenced sex-specific force-time curve characteristics during SLDJs. Although jump height and the RSI remained consistent, females exhibited a significant decline in spring-like correlation and a greater reduction in vGRF from peak to the lowest CoM displacement at higher drop heights. These findings suggest that females may adopt less efficient shock absorption strategies at increased drop heights, potentially increasing their risk of ACL injury. Understanding these sex-specific differences is crucial for refining injury screening and prevention strategies. Current protocols that standardize drop heights across sexes may fail to capture key biomechanical differences. This study emphasizes the need for personalized drop heights and force-time curve analyses in injury risk assessments. Future training programs should focus on improving neuromuscular control and lower limb stiffness in females to enhance impact absorption and reduce ACL injury risk.

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