

Prelanding Knee Kinematics and Landing Kinetics During Single-Leg and Double-Leg Landings in Male and Female Recreational Athletes

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Biomechanical behavior prior to landing likely contributes to anterior cruciate ligament (ACL) injuries during jump-landing tasks. This study examined prelanding knee kinematics and landing ground reaction forces (GRFs) during single-leg and double-leg landings in males and females. Participants performed landings with the dominant leg or both legs while kinematic and GRF data were collected. Single-leg landings demonstrated less time between prelanding minimal knee flexion and initial ground contact, decreased prelanding and early-landing knee flexion angles and velocities, and increased peak vertical and posterior GRFs compared with double-leg landings. Increased prelanding knee flexion velocities and knee flexion excursion correlated with decreased peak posterior GRFs during both double-leg and single-leg landings. No significant differences were observed between males and females. Prelanding knee kinematics may contribute to the increased risk of ACL injuries in single-leg landings compared with double-leg landings. Future studies are encouraged to incorporate prelanding knee mechanics to understand ACL injury mechanisms and predict future ACL injury risks. Studies of the feasibility of increasing prelanding knee flexion are needed to understand the potential role of prelanding kinematics in decreasing ACL injury risk.

Keywords: landing preparation, ACL, anterior cruciate ligament, injury

Noncontact anterior cruciate ligament (ACL) injuries often occur during unbalanced jump landings with most body weight on the injured leg,¹⁻⁴ and females have higher incidences of ACL injuries compared with males in most sports events.⁵⁻⁷ In vitro and in vivo studies have shown that anterior shear forces and compressive forces applied to the tibia at a small knee flexion angle were the primary loading mechanism of the ACL.^{8,9} As such, these ACL loading variables have been extensively quantified during jump-landing tasks to understand ACL injury risk factors and injury mechanisms.^{4,10,11} Studies have shown that single-leg landings are more likely to result in increased ACL loading than double-leg landings because of greater impact forces and decreased knee flexion angles during the landing phase.¹⁰⁻¹³ In addition, some studies found that females demonstrated lower knee flexion angles and great impact landing forces than males during jump-landing tasks,¹⁴⁻¹⁶ although some other studies did not find a sex effect on landing biomechanics.¹⁷ Understanding the biomechanical differences between landing tasks and sexes can provide information for identifying high-risk populations and developing injury prevention strategies.

Video analyses of ACL injury events have shown that ACL injuries typically occur within 50 milliseconds after the injured leg initially contacts the ground.^{18,19} Therefore, previous studies have focused on quantifying knee motion and impact ground reaction forces (GRFs) within 100 milliseconds after initial ground contact during jump-landing tasks.^{13,20} A musculoskeletal modeling study also found that peak ACL forces occurred 7–10 milliseconds after initial contact, and increasing knee flexion at initial contact decreased peak ACL forces during a single-leg landing.²¹ In the meantime, simple reaction time is greater than 100 milliseconds,²² so the abnormal mechanics that result in ACL injuries during early landing are likely the consequences of inappropriate landing

preparation instead of incorrect responses to initial ground contact. In fact, in vivo imaging studies showed that peak ACL strain occurred approximately 55 milliseconds prior to initial contact during noninjury single-leg jump-landing tasks.^{23,24} The timing of peak ACL strain also corresponded to the minimal knee flexion angle during prelanding. As knee flexion angles started to increase shortly prior to initial contact, ACL strain decreased and was lower during the landing phase compared with the prelanding phase.^{23,24} Based on these findings, researchers suggested that an athlete may be able to anticipate ground contact and increase knee flexion angles as a protective mechanism during noninjury jump-landing tasks.²⁵ However, the sensory input and motor planning of safe prelanding patterns might be disrupted and result in incorrect timing of anticipation of ground contact and increased risks of ACL injuries.²⁵

Despite the importance of prelanding knee kinematics on ACL loading, there were limited studies that compared prelanding knee kinematics during different jump-landing tasks or between sexes. Yu et al¹⁴ found that increased knee flexion velocities at initial contact negatively correlated with peak vertical and posterior GRF during double-leg landings. In addition, females demonstrated smaller knee flexion angles and angular velocities at initial contact compared with males. But these analyses were limited to double-leg landings and knee kinematics at initial contact without including the prelanding phase. Chappell et al²⁶ showed that females demonstrated decreased knee flexion angles during the later prelanding phase of a double-leg landing compared with males, and these differences likely resulted from increased quadriceps activation in females. As single-leg landings impose greater risks for ACL injuries, there is a need to further understand how prelanding mechanics might differ between single-leg and double-leg landings and between males and females, as well as how prelanding mechanics might be associated with ACL loading variables during the early-landing phase.

The first purpose of this study was to determine the differences in prelanding and landing knee kinematics and landing impact

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forces between single-leg and double-leg landings and between males and females. The second purpose was to quantify the correlation between prelanding and early-landing knee kinematics and peak vertical and posterior GRF in single-leg and double-leg landings. It was hypothesized that single-leg landings and females would demonstrate less minimal knee flexion angles and knee flexion angular velocities during prelanding and less knee flexion angles and velocities and increased peak landing forces during early landing compared with double-leg landings and males, respectively. It was also hypothesized that increased knee flexion angular velocities during prelanding would correlate with decreased peak landing forces in both single-leg and double-leg landings. The findings may help understand the mechanisms of elevated ACL injury risk in single-leg landings and females and provide information in developing movement modification strategies for ACL injury prevention.

Methods

Subjects

An effect size (Cohen *d*) of 1.36 and 0.85 was estimated for the knee flexion angle at initial contact between single-leg and double-leg landings¹³ and between males and females,¹⁴ respectively. A correlation coefficient of 0.49 was estimated for the correlation between prelanding knee flexion angular velocities and peak vertical and posterior GRF.¹⁴ Based on these estimations, a sample size of 23 males and 23 females was needed for the comparison and correlation analyses to achieve a power of 0.8 at a type I error level of 0.05. In total, 26 male and 26 female recreational athletes, who had experience in jump-landing sports and had never had a major lower extremity injury, participated in this study (females: 20.70 [2.09] y, 1.70 [0.06] m, 64.05 [9.43] kg; males: 23.22 [2.63] y, 1.78 [0.05] m, 76.58 [8.07] kg). Specific inclusion and exclusion criteria were described in a previous study.²⁷ This study was approved by the University of Wyoming Institutional Review Board. Each participant signed a consent form before data collection.

Procedure

After changing into spandex clothes and standard running shoes, participants performed a warm-up protocol.¹³ A total of 16 reflective markers were placed on the 7th cervical vertebrae, bilateral acromioclavicular joints, bilateral greater trochanters, and the dominant leg's anterior thigh, lateral and medial femoral condyles, tibia tuberosity, inferior shank, first toe, the first and fifth metatarsal, lateral and medial malleolus, and calcaneus. The dominant leg was defined as the preferred jumping leg for a longer distance. After a static trial, participants performed a minimum of 3 practice trials and 3 official trials of a jump-landing task. The jump-landing task required the participant to jump forward from a 30-cm-height box placed half of the participant's body height from the force plate and land with either both legs or the dominant leg.¹³ Eight cameras (Vicon Motion Systems Ltd) were utilized for recording kinematic data at 160 Hz. GRFs were collected using one force platform at 1600 Hz (Bertec Corporation).

Data Reduction

The fourth-order Butterworth low-pass digital filters were used to filter kinematic data at 15 Hz and force data at 100 Hz.¹³ The hip joint center was defined as a point located at 23.4% between the 2

greater trochanters.²⁸ The knee joint center was defined as the midpoint between the medial and lateral femoral condyles. The ankle joint center was defined as the midpoint between the medial and lateral malleoli. The thigh reference frame was defined by the hip joint center, knee joint center, and lateral femoral condyles. The shank reference frame was defined by the knee joint center, ankle joint center, and lateral malleolus. The 3-dimensional knee joint angles were calculated as the Cardan angles between the shank and thigh reference frames with an order of flexion/extension, adduction/abduction, and internal/external rotation.²⁹ Knee joint angles during the static trial were defined as neutral alignment and subtracted from the angles during the landing trials. The initial ground contact was defined as the frame when the vertical GRF was greater than 20 N. Screening of jump-landing trials showed minimal knee flexion angles occurred within 100 milliseconds prior to initial ground contact (Figure 1). The dependent variables during the prelanding phase, defined as within 100 milliseconds prior to initial ground contact, included the minimal knee flexion angle, timing of the minimal knee flexion angle prior to initial contact, knee flexion excursion from minimal flexion to initial contact, and average knee flexion angular velocities from minimal flexion to initial contact. The magnitude and timing of the minimal knee flexion angle were selected as they corresponded to peak ACL strain during prelanding.^{23,24} Knee flexion excursion and average knee flexion velocities were chosen to understand preparatory knee motion before landing and quantify the potential correlations between knee flexion velocities and landing forces demonstrated in a previous study.¹⁴ The dependent variables during the early-landing phase, defined as 50 milliseconds after initial contact, included the knee flexion angle at initial contact, knee flexion excursion, average knee flexion velocities, and peak vertical and posterior GRF. The peak vertical and posterior GRF were normalized by the participant's body weight. All data reductions were performed using the MATLAB 2016b software.

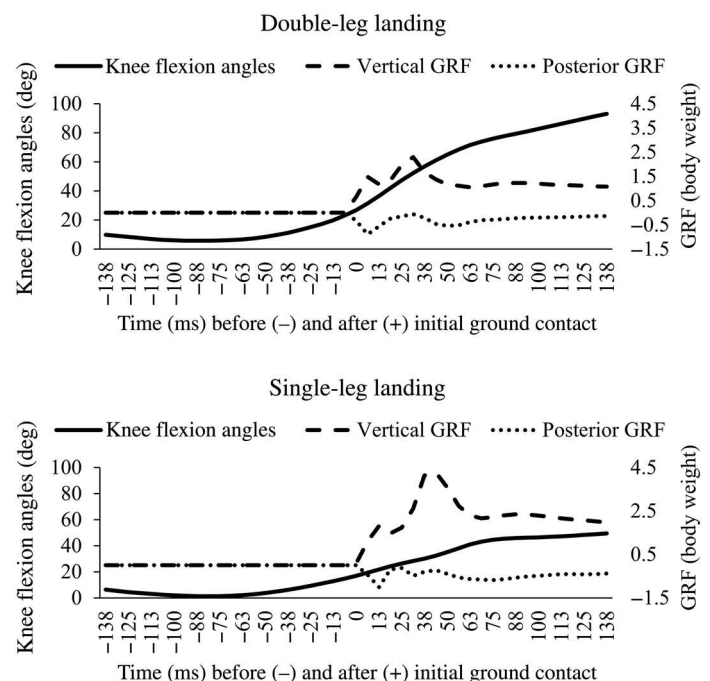


Figure 1 — An example of knee flexion angles and vertical and posterior GRFs during prelanding and early landing during single-leg and double-leg landings. GRF indicates ground reaction force.

Statistical Analysis

Dependent variables were compared between the landing conditions (double-leg and single-leg, within-participant factor) and sexes (males and females, between-participant factor) using 2-way mixed repeated measures analyses of variance, followed by independent or paired *t* tests for a significant interaction effect. A significant level of interaction effect was set at .05. Pearson correlation analyses were performed between prelanding and early-landing knee kinematics variables and peak vertical and posterior GRF. Pearson correlation coefficients smaller than .3 were considered a “weak” correlation, between .3 and .5 and greater than .5 were considered “moderate” and “strong” correlations, respectively.³⁰ The Benjamini–Hochberg procedure was performed to the main effects of analyses of variance without interaction effects, follow-up *t* tests of analyses of variance with interaction effects, and Pearson correlation analyses to control the study-wide false discovery rate at .05.³¹ The largest *P* value for statistical significance was .011 after adjusting the false discovery rate. All statistical analyses were performed using the SPSS software (version 28).

Results

For the prelanding phase, the single-leg landing resulted in decreased minimal knee flexion angles, knee flexion excursion, and angular velocities compared with the double-leg landing for both males and females (Table 1; Figure 2). Relative to the double-leg landing, the single-leg landings also resulted in shorter time

from minimum knee flexion to landing. During the early-landing phase, the single-leg landing resulted in decreased knee flexion angles at initial contact, knee flexion excursion, and angular velocities, as well as increased peak and posterior vertical GRF compared with the double-leg landing for both males and females. No significant sex effects were observed for any dependent variables, although 2 trends of significant differences ($P < .1$) were observed. Males tended to have greater minimal knee flexion angles and less knee flexion velocities during the prelanding phase than females for both single-leg and double-leg landings (Table 1).

For the correlation analyses, increased prelanding knee flexion velocities and knee flexion excursion significantly correlated with decreased peak posterior GRF during both single-leg and double-leg landings (Table 2; Figures 3 and 4). Knee flexion angles at initial contact also negatively correlated with peak posterior GRF during double-leg landings. A total of 2 moderate trends of significant correlations ($P \leq .024$, $r > .3$) were observed between prelanding minimal knee flexion angles and peak posterior GRF during single-leg landings and between average knee flexion velocities and peak vertical GRF during double-leg landings.

Secondary correlation analyses were performed for males and females separately. Significantly negative correlations between prelanding knee flexion velocities and peak posterior GRF were observed for both males and females during single-leg landings and for males during double-leg landings. Significantly negative correlations between knee flexion excursion and peak posterior GRF were observed for males during double-leg landings and for females during single-leg landings. For males, timing of minimal knee flexion angles during prelanding and knee flexion angles at

Table 1 Mean (SDs) of Dependent Variables, *P* Values of ANOVAs, and Results of Comparisons for Different Landing Conditions and Sexes

	Double-leg landing		Single-leg landing		P values of ANOVA		
	Males	Females	Males	Females	Landing condition	Sex	Interaction
Prelanding							
Timing of minimal knee flexion angles, ms	57.8 (15.9) A	52.2 (17.9)	41.9 (20.0) B	46.2 (15.3)	<.001	.875	.042
Minimal knee flexion angles, °	8.0 (5.1) A	6.0 (4.9) A	4.9 (5.2) B	2.2 (4.7) B	<.001	.080	.546
Knee flexion excursion, °	10.0 (5.6) A	10.4 (4.0) A	5.3 (3.9) B	6.5 (3.6) B	<.001	.448	.527
Average knee flexion velocities, °/s	164.3 (56.1) A	197.4 (54.1) A	112.7 (53.3) B	133.3 (54.1) B	<.001	.038	.455
Early landing							
Knee flexion angles at initial landing, °	18.0 (6.9) A	16.4 (5.7) A	10.2 (6.1) B	8.7 (4.6) B	<.001	.325	.835
Knee flexion excursion, °	36.5 (3.3) A	37.7 (3.6) A	29.5 (3.4) B	27.3 (5.4) B	<.001	.608	.003
Average knee flexion velocities, °/s	729.9 (65.2) A	754.7 (72.7) A	589.6 (67.4) B	545.1 (107.0) B	<.001	.608	.003
Peak vertical forces (body weight)	3.1 (0.7) B	3.0 (0.8) B	4.3 (0.8) A	4.6 (0.6) A	<.001	.686	.034
Peak posterior forces (body weight)	−0.8 (0.2) B	−0.8 (0.2) B	−1.2 (0.2) A	−1.2 (0.2) A	<.001	.690	.435

Abbreviation: ANOVA, analysis of variance. Note: “A” was significantly greater than “B” between the 2 landing conditions for each sex. No significant sex effects were observed for either landing conditions for any variable after the adjustment of the type I error rate. Significant ANOVA effects are indicated in bold.

initial contact negatively correlated with peak posterior GRF during double-leg landings, while prelanding minimal knee flexion angles positively correlated with peak posterior GRF during single-leg landings (Appendix).

Discussion

The first purpose was to identify the differences in prelanding and landing knee kinematics and landing impact forces between 2 jump-landing tasks and sexes. The results supported the hypothesis that single-leg landings would demonstrate smaller minimal knee flexion angles and velocities during prelanding and less knee flexion angles and velocities and increased peak forces during early landing compared with double-leg landings. Previous studies have well documented the decreased knee flexion angles and increased impact forces during early landing for single-leg landings compared with double-leg landings,^{10–13} supporting the observation that most ACL injuries occur during single-leg landings or landings with most body weight placed on one leg.^{1–4} The current findings showed that not only the landing phase but also the

prelanding phase might predispose athletes to higher risks for ACL injuries during single-leg landings. The goal of the landing task was to decelerate the linear momentum through the control of the body movements and the modulation of GRF. Based on the impulse–momentum relationship, decreasing impact GRF likely requires a longer landing time that can be accomplished through a greater joint excursion. In the meantime, increasing joint angles generally increase the moment arms from the GRF to the knee and hip joints, requiring greater efforts from muscles to generate active internal joint moments. For double-leg landings, the demand for increased active internal knee moments associated with increased knee angles would be less challenging as the body weight and landing forces were supported by 2 legs. On the other hand, knee strength is likely a limiting factor in how much knee flexion an individual can achieve during single-leg squats and landings.^{13,32} For single-leg landings, participants decreased knee joint angles to constrain the external moments imposed on the knee joint to prevent joint collapse and falling. The decreased knee flexion at initial contact was the consequence of decreased knee flexion angles and velocities during prelanding. Single-leg landing also generally demonstrated less time between minimal knee flexion angles and initial contact, indicating participants waited closer to initial contact to start to flex the knee. The average timing of minimal knee flexion angles (~55 ms) during double-leg landings was consistent with previous studies,^{23,24} but the average timing of minimal knee flexion angles decreased to approximately 44 milliseconds during single-leg landings. This decreased margin suggests that single-leg landings might be more susceptible to midflight perturbation, which might result in errors in anticipation of ground contact and therefore landings without active knee flexion during prelanding. High impact forces acting on a close-to-extension knee that is not flexing would present a dangerous scenario for ACL injuries. Overall, the decreased prelanding knee flexion angles and velocities and the later timing of knee flexion initiation are likely additional contributors to the increased injury risk of ACL injuries for single-leg landings.

The results did not support the hypotheses regarding sex differences in prelanding and landing mechanics. While there was a trend of decreased prelanding minimal knee flexion angles in females (Figure 2), this small difference was not detected as statistical significance based on the current sample size. Females demonstrate increased ACL injury rates compared with males in

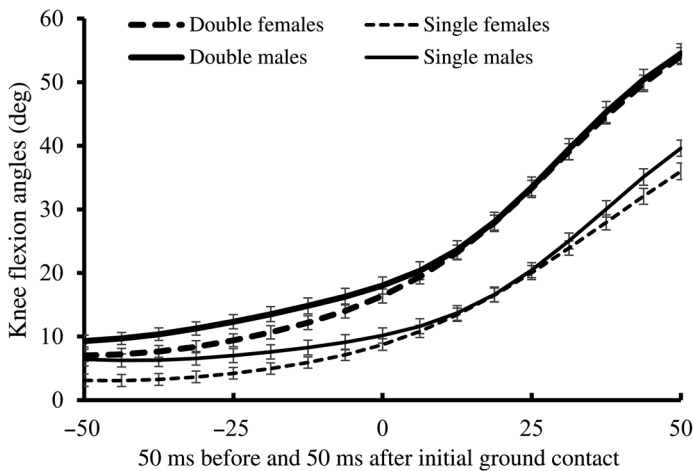


Figure 2 — Ensemble curves (means $\pm$ SEs of the means) of knee flexion angles 50 milliseconds before and after initial ground contact during single-leg and double-leg landings.

Table 2 Pearson Correlation Coefficients (*P* Values) Between Kinematic Variables and Peak Ground Reaction Forces During 2 Jump-Landing Tasks

	Peak vertical ground reaction force (body weight)		Peak posterior ground reaction force (body weight)	
	Double-leg landing	Single-leg landing	Double-leg landing	Single-leg landing
Prelanding				
Timing of minimal knee flexion angles	.22 (.127)	.20 (.167)	-.12 (.399)	-.24 (.087)
Minimal knee flexion angles	-.11 (.441)	-.09 (.529)	-.19 (.168)	.31 (.024)
Knee flexion excursion	-.11 (.422)	.11 (.442)	-.35 (.011)	-.36 (.008)
Average knee flexion velocities	-.32 (.022)	.01 (.925)	-.38 (.005)	-.46 (<.001)
Initial contact				
Knee flexion angles	-.17 (.217)	-.01 (.950)	-.42 (.002)	.04 (.756)
Early landing				
Average knee flexion velocities	-.10 (.491)	-.00 (.987)	-.25 (.074)	.12 (.380)

Significant correlations are indicated in bold.

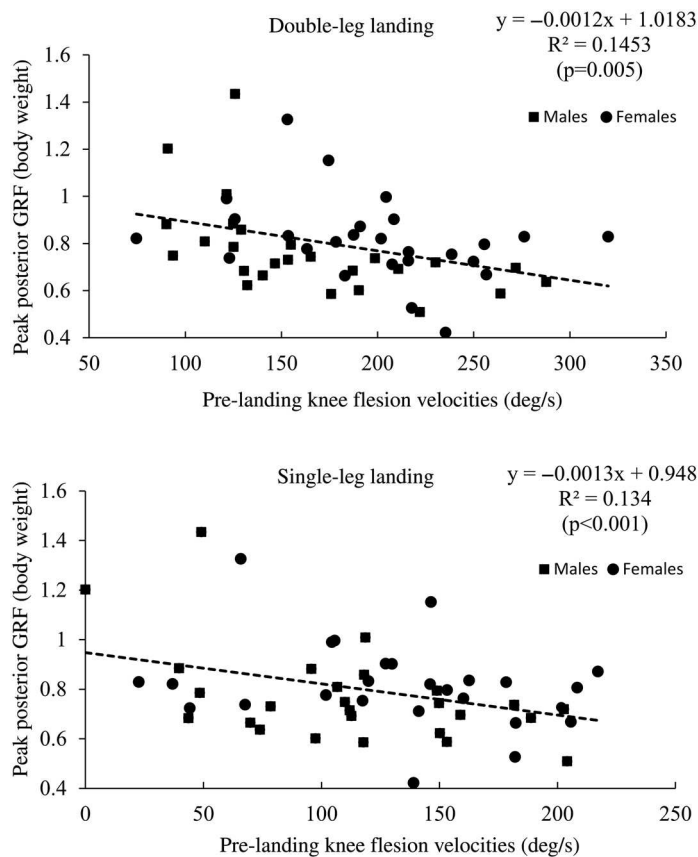


Figure 3 — Correlations between prelanding knee flexion velocities and peak posterior GRFs during single-leg and double-leg landings. GRF indicates ground reaction force.

most sports events.^{5–7} Some studies have shown that females demonstrated decreased knee flexion angles during prelanding and early landing and increased landing forces compared with males,^{14–16,26} while other studies did not find sex differences during landing tasks.¹⁷ These discrepancies could be caused by different populations, landing tasks, or the physical capabilities of participants. For example, 3 previous studies chose a stop-jump task with a self-selected approaching speed as the landing task,^{14,16,26} while this study used a drop-landing task to better control the landing parameters. Using the same absolute drop for both males and females might also introduce greater relative demands on females who generally demonstrate lower jump height. In fact, a previous study showed that potential sex differences in landing mechanics varied between a drop-vertical jump and a stop-jump, with the stop-jump resulting in more sex differences.³³ In summary, males and females demonstrated similar prelanding and landing mechanics during the current single-leg and double-leg landings with precise control of the drop height and jump distance.

Another purpose was to evaluate the correlation between prelanding and early-landing knee kinematics and impact landing forces. The hypothesis was partially supported, as the results showed significant negative correlations between prelanding knee angular velocities and peak posterior GRF but not for peak vertical GRF during both single-leg and double-leg landings. A previous study observed that knee flexion velocities at initial contact negatively correlated with both peak posterior and vertical GRF.¹⁴ The inconsistencies for vertical GRF could be due to

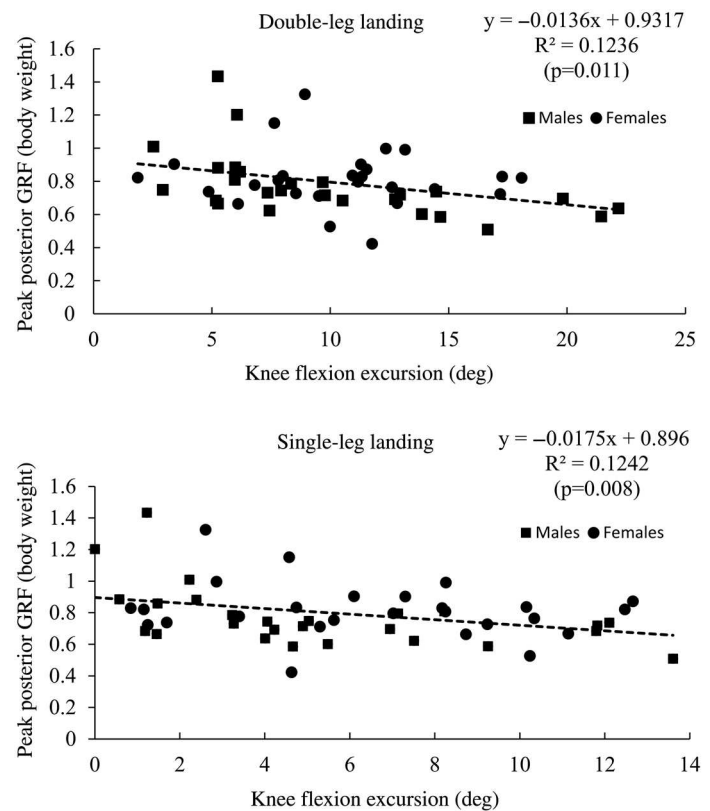


Figure 4 — Correlations between knee flexion excursion and peak posterior GRFs during single-leg and double-leg landings. GRF indicates ground reaction force.

different landing tasks and variables used for analyses, as the previous study evaluated knee flexion velocities at initial contact in a stop-jump task. Among ankle plantar flexion, knee extension, and hip extension, knee extension was the only motion that moved the foot forward relative to the ground to actively generate posterior GRF during early landing. Therefore, it was reasonable to observe a more important role of knee flexion velocities on peak posterior GRF compared to peak vertical GRF during the current forward jump-landing task. On the other hand, the hip and ankle joints might play a more important role in the vertical direction. During the landing task, a greater posterior GRF may be associated with a greater quadriceps muscle force to maintain the same knee joint resultant moment, resulting in greater anterior shear forces applied to the knee, particularly at a small knee flexion angle.³⁴ Increased prelanding knee flexion velocities indicated a more active knee flexion motion to prepare for a soft landing to stop the body in the anterior–posterior direction with decreased peak posterior GRF.

Meanwhile, the correlations further showed that knee flexion excursion had significant negative correlations with peak posterior GRF. As angular velocities were calculated as the quotient of knee flexion excursion and time, the correlations suggested the increased knee flexion velocities were more likely caused by increased knee flexion excursion instead of less time between prelanding minimal knee flexion and initial contact. For double-leg landings, increased knee flexion angles at initial contact appeared to play an important role in decreasing peak posterior GRF based on the correlation results. For single-leg landings, prelanding minimal knee flexion angles showed a trend to be associated with decreased posterior GRF, suggesting some participants likely decreased the minimal

flexion angle to achieve a great knee flexion excursion during single-leg landings. These observations further support that increasing knee flexion angles at initial contact would be an effective strategy to increase prelanding velocities for double-leg landings as the knee strength is less likely a limiting factor. However, excessive knee flexion angles at initial contact might be more challenging for knee strength for single-leg landings, and some participants appeared to decrease the prelanding minimal knee flexion as a compensatory strategy to achieve the goal of increased knee flexion excursion and velocities. Therefore, different strategies might be used to achieve increased prelanding knee flexion excursion and velocities, and the strategy to decrease prelanding minimal knee flexion angles for single-leg landings might be riskier when midflight perturbation occurs. When males and females were analyzed separately, prelanding knee flexion velocities appeared to be the consistent variable negatively correlated with peak posterior GRF for most landing conditions. But, in general, males demonstrated more significant correlations between kinematics variables and peak posterior GRF compared with females. In addition to the decreased statistical power when males and females were separated into 2 groups, the greater relative performance demand imposed by the standardized drop height might have required females to utilize various and less consistent strategies to increase prelanding knee flexion velocities, resulting in less significant correlations. Overall, actively prelanding knee flexion velocities correlated with decreased peak posterior GRF, while the strategies to achieve increased velocities might be different for single-leg and double-leg landings and for males and females.

This study provided implications for practical applications. First, the differences in prelanding knee kinematics between single-leg and double-leg landings provide additional information to understand the increased ACL injury risk in single-leg landings. While previous video analyses of ACL injury events have focused on the early-landing phase to understand ACL injury mechanisms, it is recommended that future studies may incorporate the analyses of the prelanding phase. The stiff landing patterns observed during ACL injuries likely result from abnormal prelanding motion. Future prospective studies to predict ACL injuries from landing biomechanics may also consider including prelanding knee kinematics, such as the timing and magnitude of minimal knee flexion angles, as well as prelanding knee flexion velocities. Second, males and females appeared to demonstrate similar knee prelanding kinematics and landing mechanics during the controlled single-leg and double-leg landing tasks. Sex differences should not be assumed for all landing tasks simply because of higher ACL injury rates in females. Future studies are needed to examine potential sex differences in prelanding mechanics in more sports-specific tasks or event jump-landing tasks with perturbation and cognitive challenges.^{25,35} Third, active prelanding knee flexion velocities rather than knee flexion angles at a specific time likely played an important role in decreasing posterior GRF. While previous training strategies have emphasized increasing knee flexion angles during the landing phase, increased prelanding knee flexion velocities should also be encouraged. Increasing knee flexion angles throughout the prelanding and early-landing phases provides an injury prevention strategy that directly targets protective knee motion associated with decreased ACL loading. The decreased GRF associated with increased knee flexion also provides secondary protective effects on the ACL. Meanwhile, increasing prelanding knee flexion velocities could be more challenging for single-leg landings, and concurrent strength and neuromuscular training programs might be needed to promote active prelanding knee flexion without falling.

There were several limitations in the study. First, only one single-leg and one double-leg landing task with controlled landing heights and distances were included. The landing preparation is likely to be affected by different landing tasks. Second, the correlation analyses indicated significant relationships between knee flexion velocities and peak posterior GRF, but the cause-effect relationship between them needs to be further established. Third, while knee flexion angles and impact forces have been documented as the primary ACL loading mechanisms during landing, the actual ACL loading was not directly assessed. Finally, the absolute drop height was the same for both males and females. Future studies may consider using a drop height relative to each participant's jump height. More participants are also needed to analyze the correlations between prelanding kinematics and landing kinetics with separated male and female groups.

In conclusion, the decreased prelanding knee flexion angles and velocities and the later timing of knee flexion initiation may contribute to the increased risk of ACL injuries during single-leg landings compared with double-leg landings. Males and females demonstrated similar prelanding and landing mechanics during the current single-leg and double-leg landings with precise control of the drop height and jump distance. Actively prelanding knee flexion velocities correlated with decreased peak posterior GRF, while the strategies to achieve increased velocities might be different for single-leg and double-leg landings. Future studies are encouraged to incorporate prelanding knee mechanics to understand ACL injury mechanisms and predict future ACL injury risks. Studies of the feasibility of increasing prelanding knee flexion are needed to understand the potential role of prelanding kinematics in decreasing ACL injury risk.

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References

1. Stuelcken MC, Mellifont DB, Gorman AD, Sayers MG. Mechanisms of anterior cruciate ligament injuries in elite women's netball: a systematic video analysis. *J Sports Sci.* 2016;34(16):1516–1522. doi:10.1080/02640414.2015.1121285
2. Waldén M, Krosshaug T, Bjørneboe J, Andersen TE, Faul O, Häggglund M. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. *Br J Sports Med.* 2015;49(22):1452–1460. doi:10.1136/bjsports-2014-094573
3. Dai B, Mao D, Garrett WE, Yu B. Anterior cruciate ligament injuries in soccer: loading mechanisms, risk factors, and prevention programs. *J Sport Health Sci.* 2014;3(4):299–306. doi:10.1016/j.jshs.2014.06.002
4. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573–578. doi:10.3928/0147-7447-20000601-15
5. Montalvo AM, Schneider DK, Yut L, et al. "What's my risk of sustaining an ACL injury while playing sports?" A systematic review with meta-analysis. *Br J Sports Med.* 2019;53(16):1003–1012. doi:10.1136/bjsports-2016-096274

6. Montalvo AM, Schneider DK, Webster KE, et al. Anterior cruciate ligament injury risk in sport: a systematic review and meta-analysis of injury incidence by sex and sport classification. *J Athl Train*. 2019;54(5):472–482. doi:[10.4085/1062-6050-407-16](https://doi.org/10.4085/1062-6050-407-16)
7. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005;33(4):524–531. doi:[10.1177/0363546504269937](https://doi.org/10.1177/0363546504269937)
8. Beaulieu ML, Ashton-Miller JA, Wojtys EM. Loading mechanisms of the anterior cruciate ligament. *Sports Biomech*. 2023;22(1):1–29. doi:[10.1080/14763141.2021.1916578](https://doi.org/10.1080/14763141.2021.1916578)
9. Cerulli G, Benoit DL, Lamontagne M, Caraffa A, Liti A. In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: case report. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(5):307–311. doi:[10.1007/s00167-003-0403-6](https://doi.org/10.1007/s00167-003-0403-6)
10. Yeow CH, Lee P, Goh J. Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. *Knee*. 2010;17(2):127–131. doi:[10.1016/j.knee.2009.07.015](https://doi.org/10.1016/j.knee.2009.07.015)
11. Wang L. The lower extremity biomechanics of single- and double-leg stop-jump tasks. *J Sports Sci Med*. 2011;10(1):151–156. PubMed ID: [24149308](https://pubmed.ncbi.nlm.nih.gov/24149308/)
12. Yeow CH, Lee PVS, Goh JCH. An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Hum Mov Sci*. 2011;30(3):624–635. doi:[10.1016/j.humov.2010.11.010](https://doi.org/10.1016/j.humov.2010.11.010)
13. Li L, Baur M, Baldwin K, et al. Falling as a strategy to decrease knee loading during landings: implications for ACL injury prevention. *J Biomech*. 2020;109:109906. doi:[10.1016/j.jbiomech.2020.109906](https://doi.org/10.1016/j.jbiomech.2020.109906)
14. Yu B, Lin C, Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech*. 2006;21(3):297–305. doi:[10.1016/j.clinbiomech.2005.11.003](https://doi.org/10.1016/j.clinbiomech.2005.11.003)
15. Salci Y, Kentel BB, Heycan C, Akin S, Korkusuz F. Comparison of landing maneuvers between male and female college volleyball players. *Clin Biomech*. 2004;19(6):622–628. doi:[10.1016/j.clinbiomech.2004.03.006](https://doi.org/10.1016/j.clinbiomech.2004.03.006)
16. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech*. 2001;16(5):438–445. doi:[10.1016/S0268-0033\(01\)00019-5](https://doi.org/10.1016/S0268-0033(01)00019-5)
17. Beaulieu ML, McLean SG. Sex-dimorphic landing mechanics and their role within the noncontact ACL injury mechanism: evidence, limitations and directions. *Sports Med Arthrosc Rehabil Ther Technol*. 2012;4(1):10. doi:[10.1186/1758-2555-4-10](https://doi.org/10.1186/1758-2555-4-10)
18. Dai B, Mao M, Garrett WE, Yu B. Biomechanical characteristics of an anterior cruciate ligament injury in javelin throwing. *J Sport Health Sci*. 2015;4(4):333–340. doi:[10.1016/j.jshs.2015.07.004](https://doi.org/10.1016/j.jshs.2015.07.004)
19. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218–2225. doi:[10.1177/0363546510373570](https://doi.org/10.1177/0363546510373570)
20. Kristianslund E, Faul O, Bahr R, Myklebust G, Krosshaug T. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. *Br J Sports Med*. 2014;48(9):779–783. doi:[10.1136/bjsports-2012-091370](https://doi.org/10.1136/bjsports-2012-091370)
21. Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, O'Connor KM. The effects of single-leg landing technique on ACL loading. *J Biomech*. 2011;44(10):1845–1851. doi:[10.1016/j.jbiomech.2011.04.010](https://doi.org/10.1016/j.jbiomech.2011.04.010)
22. Hanson JV, Whitaker D, Heron J. Preferential processing of tactile events under conditions of divided attention: effects of divided attention on reaction time. *Neuroreport*. 2009;20(15):1392. doi:[10.1097/WNR.0b013e3283319e25](https://doi.org/10.1097/WNR.0b013e3283319e25)
23. Englander ZA, Lau BC, Wittstein JR, Goode AP, DeFrate LE. Patellar tendon orientation and strain are predictors of ACL strain in vivo during a single-leg jump. *Orthop J Sports Med*. 2021;9(3):2325967121991054. doi:[10.1177/2325967121991054](https://doi.org/10.1177/2325967121991054)
24. Englander ZA, Baldwin ELIII, Smith WA, Garrett WE, Spritzer CE, DeFrate LE. In vivo anterior cruciate ligament deformation during a single-legged jump measured by magnetic resonance imaging and high-speed biplanar radiography. *Am J Sports Med*. 2019;47(13):3166–3172. doi:[10.1177/0363546519876074](https://doi.org/10.1177/0363546519876074)
25. Hughes G, Dai B. The influence of decision making and divided attention on lower limb biomechanics associated with anterior cruciate ligament injury: a narrative review. *Sports Biomech*. 2023;22(1):30–45. doi:[10.1080/14763141.2021.1898671](https://doi.org/10.1080/14763141.2021.1898671)
26. Chappell JD, Creighton RA, Giuliani C, Yu B, Garrett WE. Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2007;35(2):235–241. doi:[10.1177/0363546506294077](https://doi.org/10.1177/0363546506294077)
27. Davis DJ, Hinshaw TJ, Critchley ML, Dai B. Mid-flight trunk flexion and extension altered segment and lower extremity joint movements and subsequent landing mechanics. *J Sci Med Sport*. 2019;22(8):955–961. doi:[10.1016/j.jsams.2019.03.001](https://doi.org/10.1016/j.jsams.2019.03.001)
28. Bennett HJ, Shen G, Weinhandl JT, Zhang S. Validation of the greater trochanter method with radiographic measurements of frontal plane hip joint centers and knee mechanical axis angles and two other hip joint center methods. *J Biomech*. 2016;49(13):3047–3051. doi:[10.1016/j.jbiomech.2016.06.013](https://doi.org/10.1016/j.jbiomech.2016.06.013)
29. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105(2):136–144. doi:[10.1115/1.3138397](https://doi.org/10.1115/1.3138397)
30. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Lawrence Erlbaum Associates; 1988:20–26.
31. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J R Stat Soc Series B*. 1995;57(1):289–300. doi:[10.2307/2346101](https://doi.org/10.2307/2346101)
32. Sato H, Kusayanagi K, Kondo Y, Kamide N, Shiba Y, Takashima A. Knee extensor strength assessed using a vertical squat and a simple geometric model to calculate joint torque: an evaluation of validity and clinical utility. *Geriatr Gerontol Int*. 2018;18(7):1125–1131. doi:[10.1111/ggi.13299](https://doi.org/10.1111/ggi.13299)
33. Peebles AT, Dickerson LC, Renner KE, Queen RM. Sex-based differences in landing mechanics vary between the drop vertical jump and stop jump. *J Biomech*. 2020;105:109818. doi:[10.1016/j.jbiomech.2020.109818](https://doi.org/10.1016/j.jbiomech.2020.109818)
34. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med*. 2007;41(suppl 1):i47–i51. doi:[10.1136/bjsm.2007.037192](https://doi.org/10.1136/bjsm.2007.037192)
35. Song Y, Li L, Hughes G, Dai B. Trunk motion and anterior cruciate ligament injuries: a narrative review of injury videos and controlled jump-landing and cutting tasks. *Sports Biomech*. 2023;22(1):46–64. doi:[10.1080/14763141.2021.1877337](https://doi.org/10.1080/14763141.2021.1877337)

Appendix: Pearson Correlation Coefficients (*P* Values) of Kinematic Variables With Peak Ground Reaction Forces During 2 Jump-Landing Tasks for Males and Females

	Peak vertical ground reaction force (body weight)				Peak posterior ground reaction force (body weight)			
	Double-leg landing		Single-leg landing		Double-leg landing		Single-leg landing	
	Males	Females	Males	Females	Males	Females	Males	Females
Prelanding								
Timing of minimal knee flexion angles, ms	.09 (.67)	.30 (.14)	.13 (.54)	.26 (.21)	-.42 (.03)	.22 (.29)	-.19 (.35)	-.31 (.13)
Minimal knee flexion angles, °	-.08 (.70)	-.18 (.38)	-.00 (.99)	-.09 (.66)	-.11 (.59)	-.25 (.22)	.54 (.004)	.10 (.61)
Knee flexion excursion, °	-.25 (.22)	.06 (.77)	-.04 (.85)	.24 (.24)	-.54 (.004)	-.09 (.68)	-.27 (.18)	-.46 (.02)
Average knee flexion velocities, °/s	-.43 (.03)	-.19 (.35)	-.18 (.39)	.15 (.45)	-.53 (.005)	-.33 (.10)	-.44 (.02)	-.49 (.01)
Initial contact								
Knee flexion angles, °	-.26 (.20)	-.11 (.59)	-.03 (.89)	.09 (.66)	-.52 (.007)	-.28 (.17)	.29 (.15)	-.25 (.22)
Early-landing								
Average knee flexion velocities, °/s	.12 (.55)	-.25 (.21)	.29 (.15)	-.14 (.51)	-.37 (.07)	-.19 (.35)	.01 (.98)	.20 (.34)

Significant correlations are indicated in bold.