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Falling decreased anterior cruciate ligament loading variables during single-leg landings after mid-flight external trunk perturbation

Yu Song [a], Ling Li [b], Jacob Layer [b], Gerwyn Hughes [c], Derek Smith [b], Margaret Wilson [d], Qin Zhu [b], Boyi Dai [b,*]

[a] Department of Health, Sport & Exercise Sciences, University of Kansas, Lawrence, KS 66045, USA
[b] Division of Kinesiology and Health, University of Wyoming, Laramie, WY 82071, USA
[c] Department of Kinesiology, University of San Francisco, San Francisco, CA 94117, USA
[d] Department of Theatre and Dance, University of Wyoming, Laramie, WY 82071, USA

A R T I C L E I N F O

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A B S T R A C T

Mid-flight external upper-trunk perturbation is associated with increased anterior cruciate ligament (ACL) injury risk during landing. This study aimed to assess the effect of natural, soft, and falling landing techniques on knee mechanics and vertical ground reaction forces (VGRF) during single-leg landings with/without mid-flight medial–lateral external upper-trunk pushing perturbation. Twenty-eight participants performed single-leg landings using the three landing techniques with/without mid-flight pushing perturbation. The perturbation was created by a customized apparatus releasing a slam ball and pushing the participants near the peak jump height at the upper trunk. Perturbation resulted in significantly greater lateral trunk bending angles, knee flexion angles at initial contact, peak knee abduction angles, and peak knee adduction moments compared to no perturbation. The falling condition significantly demonstrated the greatest lateral trunk bending angles, knee flexion angles, and peak knee external rotation moments and the smallest peak knee abduction angles, peak VGRF, and peak knee extension moments compared to natural/soft landings regardless of perturbation conditions. Mid-flight external perturbation resulted in variables associated with greater ACL loading during single-leg landings. Falling demonstrated variables associated with smaller ACL loading, particularly for perturbation conditions. Incorporating falling techniques into jump-landing training programs may guide players to safely fall on the ground when perturbation occurs. Falling provides an alternative strategy to potentially decrease indirect contact ACL injury risk when the sports environment allows.

1. Introduction

Anterior cruciate ligament (ACL) ruptures are more likely to occur in team sports due to the complex sports movements and environments which involve cognitive and physical interactions among different players and external objects (Hughes & Dai, 2023; Montalvo et al., 2019; Song et al., (2023a)). The negative consequences following ACL injuries include extensive absence from playing (Zampogna et al., 2021), impaired neuromuscular function (Tayfur et al., 2021), and elevated risks of knee osteoarthritis (Poulsen et al., 2019). One of the frequent ACL rupture scenarios is when a player lands with a single leg (Belcher et al., 2022; Della Villa et al., 2020; Montgomery et al., 2018) in a suboptimal landing posture, commonly characterized as laterally bent trunk to the injured leg, with the injured knee supporting most of the body weight in an extended and abducted position (Boden & Sheehan, 2022). Such posture is consistent with increased ACL loading (Beaulieu et al., 2023; Boden & Sheehan, 2022). Both *in vivo* and *in vitro* studies have suggested that the primary ACL loading mechanism is the anterior tibial shear force applied to an almost fully extended knee (Beaulieu et al., 2023; Boden & Sheehan, 2022; Englander et al., 2022). Internal tibial moments and knee abduction moments are also identified as loading mechanisms of the ACL (Beaulieu et al., 2023; Boden & Sheehan, 2022; Englander et al., 2022).

While a majority of ACL ruptures are believed to occur within 100 ms after initial ground contact (IC) (Dai et al., 2015b; Koga et al., 2010; Sasaki et al., 2018) without external objects contacting the injured knee (non-contact mechanism), contact with body parts other than the injured knee is commonly observed prior to or near the estimated ACL

* Corresponding author at: Division of Kinesiology and Health, University of Wyoming, Laramie, WY 82071, USA.
E-mail address: bdai@uwyo.edu (B. Dai).

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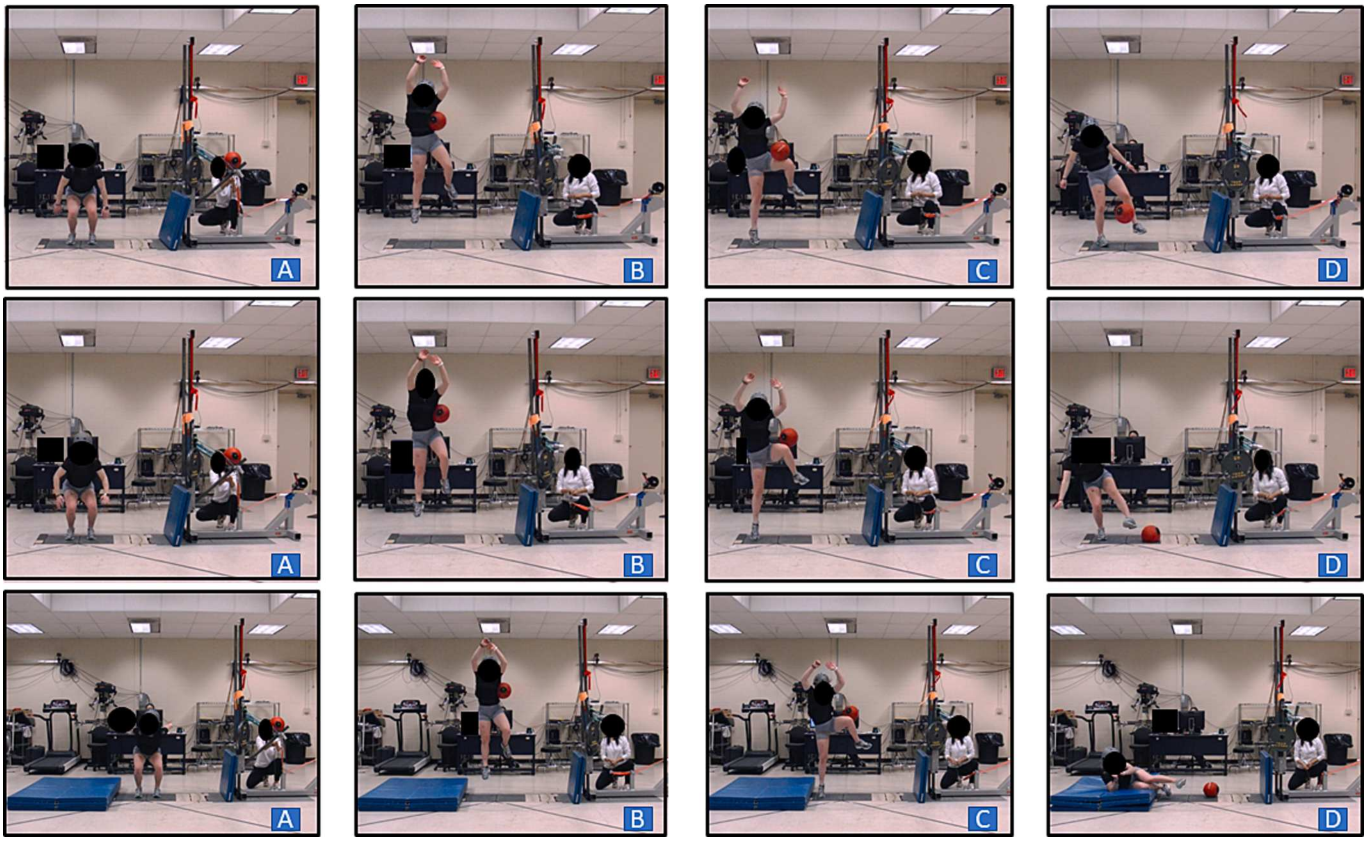

Fig. 1. Anterior view of natural landing (top row), soft landing (middle row), and falling after landing (bottom row) with upper trunk perturbation applied to the participant's left side. A: double-leg jumping, B: ball contact near the peak jump height, C: sing-leg landing at initial ground contact, D: single-leg landing.

injury time (indirect contact mechanism) (Hughes & Dai, 2023; Song et al., (2023a)). Specifically, video analyses of ACL injuries in multiple team sports have shown that 8–60 % of ACL injuries involve contact with the trunk and/or arm before or near the time of injury (Song et al., (2023a)). Different contact scenarios may include players being pushed, held by, or colliding with other players or sports equipment, such as the basketball rim or field hockey sticks. The high ACL injury rates associated with indirect contact place an urgent need to understand indirect ACL injury mechanisms and develop effective movement strategies to decrease ACL loading under indirect contact.

Previous studies quantified the effect of mid-flight medial–lateral external trunk perturbation on jump-landing mechanics (Song et al., (2023c); Yom et al., 2014). Mid-flight lateral pulling perturbation to the upper-trunk resulted in greater ground reaction forces (GRF) and smaller knee flexion angles for the leg ipsilateral to the pulling perturbation direction (Yom et al., 2014). A recent study quantified the effect of mid-flight medial–lateral pushing perturbation locations and directions on bilateral landing mechanics (Song et al., (2023c)). The pushing perturbation increased peak vertical GRF (VGRF) and knee moments and decreased knee flexion angles for the leg contralateral to the perturbation direction. Additionally, the upper-trunk perturbation resulted in greater increases in these variables compared to the lower-trunk perturbation. While the biomechanical connection between medial–lateral trunk perturbation and landings with greater peak GRF, smaller knee flexion angles, greater knee abduction angles, and greater knee extension and adduction moments associated with greater ACL loading, have been identified, the next step is to develop effective strategies to decrease ACL loading variables under such scenarios.

In fact, no studies have investigated the strategies to reduce ACL loading following mid-flight medial–lateral external trunk perturbation. Yet, several researchers reported that teaching and training individuals to adopt movement patterns could lower ACL injury risk during landings without perturbation (Hewett et al., 2016; Song et al., 2022). Participants demonstrated greater knee flexion angles, smaller peak knee abduction angles, smaller peak VGRF, and smaller estimated peak ACL forces when they attempted to land softly during controlled landings (Dai et al., 2015a; Laughlin et al., 2011; Li et al., 2020). Furthermore, safe falling, defined as initially landing softly and then smoothly falling forward and rolling toward the hands and shoulders, has been suggested as a more effective technique to decrease ACL loading variables compared to soft landing when landing and decelerating from forward jumps (Li et al., 2020). For example, roll landing is effectively performed by parkour athletes when they jump over a distance from the jumping to the landing position (Dai et al., 2020). The effectiveness of soft landings and falling has only been observed in jump-landing tasks without mid-flight perturbation. Quantifying the potential effects of soft landing and falling techniques on variables associated with ACL loading will provide evidence for jump-landing training with mid-flight external perturbation with the goal of ultimately reducing indirect contact ACL injuries.

Therefore, this study aimed to assess the effect of natural landing, soft landing, and falling techniques on variables associated with ACL loading during single-leg landing with or without mid-flight medial–-lateral external pushing perturbation to the upper-trunk among non-injured recreational athletes. It was hypothesized that mid-flight external upper-trunk perturbation would result in greater ACL loading variables in all landing techniques compared to no-perturbation conditions. In addition, soft landing and falling would result in smaller ACL loading variables compared to natural landing in both perturbation and no-perturbation conditions. Furthermore, the falling techniques would be more effective in decreasing ACL loading variables compared to the soft landing, particularly in perturbation conditions.

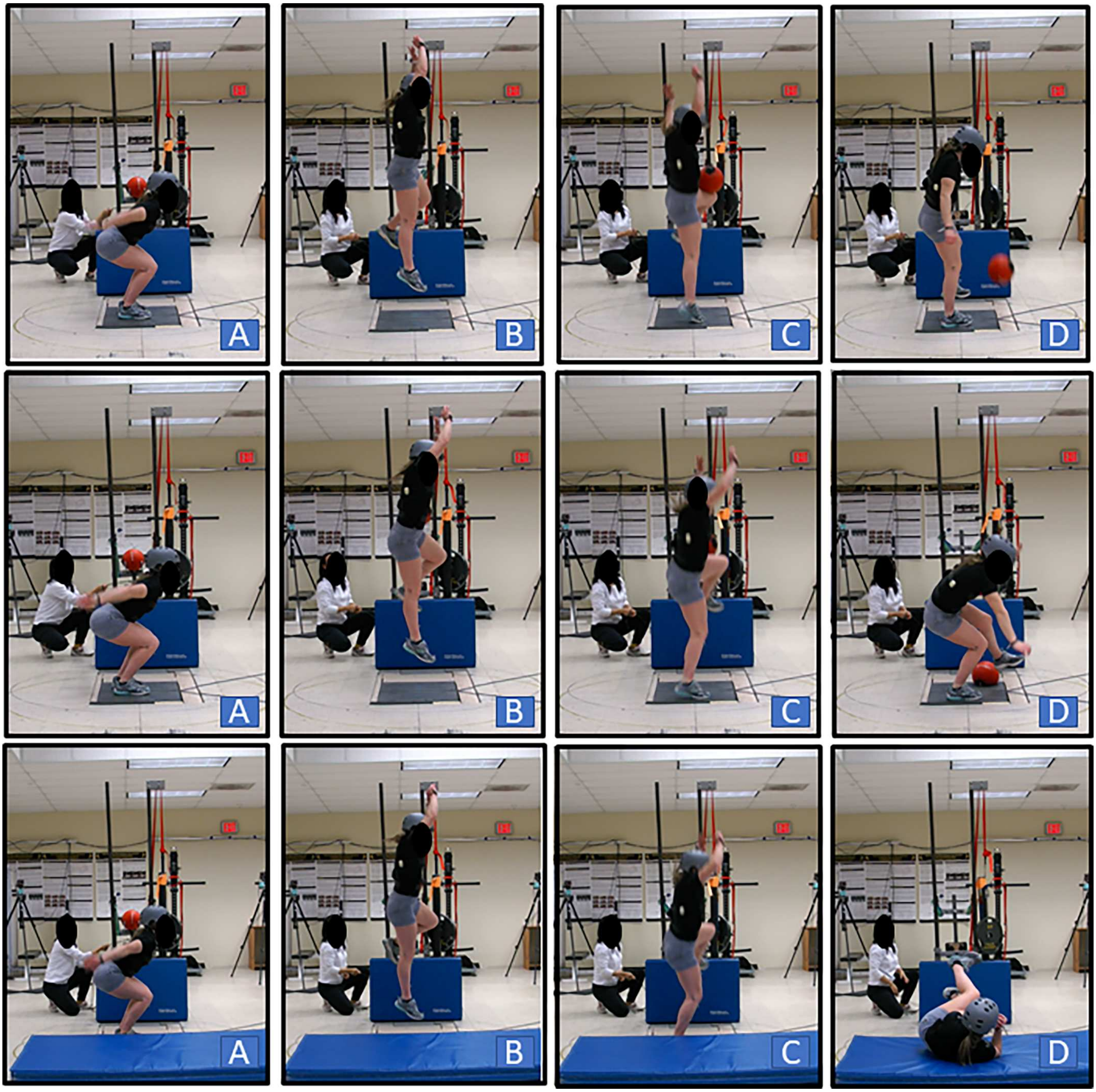

Fig. 2. Side view of natural landing (top row), soft landing (middle row), and falling after landing (bottom row) with upper trunk perturbation applied to the participant's left side. A: double-leg jumping, B: ball contact near the peak jump height, C: single-leg landing at initial ground contact, D: single-leg landing.

2. Methods

2.1. Participants

The smallest effect sizes in peak VGRF between soft landing and falling (mean ± standard deviations: 3.6 ± 0.9 body weight (BW) versus 3.0 ± 0.7 BW) was 0.55, and between with and without perturbation (3.2 ± 0.7 BW versus 2.3 ± 0.7 BW) was 1.1 (Li et al., 2020; Song et al., (2023c)). As such, a sample size of 28 was needed to achieve a power of 80 % at a type I error rate of 0.05. Twenty-eight recreational athletes participated in this study (14 males and 14 females, age: 22.0 ± 2.9 years, height: 1.7 ± 0.1 m, and mass: 71.3 ± 13.5 kg). Participants were excluded if they had previous major lower limb injuries that involved surgical treatment; had a lower limb injury that prevented participation in physical activity for more than two weeks over the last six months; or possessed any conditions that prevented them from participating at maximal effort in sporting activities. The current study was approved by the University of Wyoming Institutional Review Board, and informed consent was provided before participation.

2.2. Protocol

Participants were asked to perform a generalized warm-up protocol (Davis et al., 2019). Jump height was quantified using the difference between one standing trial and three jumping trials using a Vertec (Columbus, OH). The standing trial involved participants pushing the

Table 1
Means ± standard deviations and p-values of repeated-measures ANOVAs in dependent variables.

		Landing Techniques			P-values for repeated-measures ANOVAs		
		Natural Landing	Soft Landing	Falling Landing	Perturbation	Landing Technique	Interaction
Jump Height (m)	No Perturbation	0.37 ± 0.09	0.36 ± 0.10	0.37 ± 0.10	0.516	0.302	0.140
	Perturbation	0.37 ± 0.10	0.37 ± 0.10	0.36 ± 0.10			
Lateral Trunk Bending at Initial Contact (°)	No Perturbation	4.9 ± 2.9^{B*}	4.4 ± 2.8^{B*}	7.3 ± 3.1^{A*}	**<0.001**	**<0.001**	0.535
	Perturbation	9.7 ± 3.2^{B*}	9.7 ± 3.2^{B*}	12.6 ± 3.3^{A*}			
Knee Flexion Angle at Initial Contact (°)	No Perturbation	10.2 ± 5.9^{B*}	11.3 ± 6.5^{B*}	12.6 ± 6.5^{A*}	**0.005**	**<0.001**	0.107
	Perturbation	11.4 ± 5.3^{B*}	12.1 ± 6.1^{B*}	14.6 ± 6.6^{A*}			
Peak Knee Flexion Angle during Landing (°)	No Perturbation	46.4 ± 8.6^{C}	49.8 ± 8.6^{B}	48.2 ± 7.8^{A*}	**<0.001**	**<0.001**	**0.002**
	Perturbation	47.4 ± 9.1^{B}	50.6 ± 8.3^{A}	52.0 ± 8.6^{A*}			
Peak Knee Abduction Angle (-) during Landing (°)	No Perturbation	−1.6 ± 2.8^{A*}	−1.2 ± 2.9^{B*}	−1.1 ± 2.7^{C*}	**<0.001**	**<0.001**	0.072
	Perturbation	−3.1 ± 2.8^{A*}	−2.8 ± 2.9^{B*}	−2.2 ± 2.8^{C*}			
Peak Knee Internal Rotation Angle during Landing (°)	No Perturbation	8.3 ± 5.7	7.2 ± 6.3	7.3 ± 7.0	0.867	0.477	0.508
	Perturbation	7.7 ± 5.5	7.3 ± 5.3	7.5 ± 7.4			
Peak Vertical GRF (BW)	No Perturbation	3.7 ± 0.7^{A*}	3.3 ± 0.7^{B*}	2.9 ± 0.7^{C}	**<0.001**	**<0.001**	**0.005**
	Perturbation	4.0 ± 0.8^{A*}	3.7 ± 0.8^{B*}	2.9 ± 0.7^{C}			
Peak Knee Extension Moment (-) during Landing (BW*BH)	No Perturbation	−0.13 ± 0.03^{A}	−0.12 ± 0.03^{B}	−0.11 ± 0.03^{C}	0.465	**<0.001**	0.868
	Perturbation	−0.13 ± 0.03^{A}	−0.12 ± 0.03^{B}	−0.11 ± 0.03^{C}			
Peak Knee Adduction Moment during Landing (BW*BH)	No Perturbation	0.010 ± 0.009*	0.008 ± 0.009*	0.007 ± 0.011*	**<0.001**	**0.001**	**0.003**
	Perturbation	0.024 ± 0.013^{A*}	0.023 ± 0.014^{A*}	0.014 ± 0.013^{B*}			
Peak Knee External Rotation Moment (-) during Landing (BW*BH)	No Perturbation	−0.015 ± 0.007^{B*}	−0.014 ± 0.007^{B*}	−0.018 ± 0.008^{A*}	**<0.001**	**<0.001**	0.096
	Perturbation	−0.009 ± 0.005^{B*}	−0.009 ± 0.006^{B*}	−0.015 ± 0.007^{A*}			

Note. Jump height: the differences in the height of the midpoint between the two greater trochanters during the static trial and each jumping trial; lateral trunk bending angles were positive when the trunk bent to the landing leg side; GRF: ground reaction force; BW: body weight; BH: body height; ^{A}, ^{B}, and ^{C}: based on paired t-tests results after Benjamini-Hochberg adjustment, ^{A} is the greatest, ^{B} is the second greatest, ^{C} is the least among landing techniques for each perturbation status; *: significantly different between no-perturbation and perturbation for each landing technique after Benjamini-Hochberg adjustment.

Table 2
Means ± standard deviations and p-values of repeated-measures ANOVAs for ball contact parameters.

	Natural Landing	Soft Landing	Falling Landing	P-values of main effect	Effect sizes (P-values) for repeated-measures ANOVAs		
					Natural vs. Soft	Natural vs. Falling	Soft vs. Falling
Horizontal Ball Velocity (m/s)	5.2 ± 0.2	5.2 ± 0.2	5.3 ± 0.2	0.738	0.12 (− − −)	0.03 (− − −)	0.12 (− − −)
Vertical Ball Velocity (m/s)	−0.03 ± 0.22^{B}	−0.05 ± 0.20^{B}	−0.13 ± 0.22^{A}	**<0.001**	0.17 (0.372)	**0.94 (<0.001)**	**0.76 (<0.001)**
Timing Offset (ms)	−5.7 ± 33.8	0.6 ± 42.6	−0.1 ± 38.5	0.497	0.21 (− − −)	0.20 (− − −)	0.02 (− − −)
Contact Location (m)	0.39 ± 0.07	0.38 ± 0.07	0.39 ± 0.07	0.120	0.17 (− − −)	0.21 (− − −)	0.43 (− − −)

Note. Timing offset: the time differences between the maximal jump height and the ball contact, a negative number indicating the ball contacted early than the maximal jump height; Contact locations: the ball position relative to hips, a positive number indicating the ball was higher than hip position; ^{A} and ^{B}: ^{A} is significantly greater than ^{B} among landing techniques after Benjamini-Hochberg adjustment.

vanes of the Vertec while standing with their feet shoulder apart. Jumping trials required participants to stand at shoulder-width and use both hands to reach the vanes of the Vertec after a maximum jump with free arm swings. The average performance of three jumping trials was calculated.

Participants performed three practice trials for each jump-landing technique to ensure they were comfortable performing each landing technique. Participants stood with feet at shoulder width apart and performed a double-leg jump vertically for maximum height and landed on one leg. Each participant always jumped from the same position during the entire data collection, controlled by the tape placed on the ground. Participants also raised both arms during mid-flight and then landed with one foot on a force platform. The landing leg was counterbalanced among participants and pre-determined based on the participant numbers. There were three landing techniques: natural landing (landed as they would in a sports environment without any instructions regarding the landing techniques), soft landing (landed as softly as possible with increased knee and hip flexion), and falling after landing (initially landed softly and then smoothly fell to the landing-leg side and rolled toward the hip, back, and shoulders on a gymnastic mat) (Figs. 1 & 2).

The mid-flight pushing perturbation was created by a customized apparatus releasing a slam ball as previously described (Song et al., (2023c)). The slam ball was designed to contact the participant's upper-trunk from the contralateral side to the landing leg near the peak jump height with a horizontal ball velocity of approximately 5 m/s. Participants wore a helmet and performed one standing and six jump-landing practice trials to become accustomed to the perturbation. A pair of sponge pads were placed around participants' thoracic cages below the armpit positions to decrease the impact forces. For the standing practice, participants stood still to experience the pushing impact. For the six jump-landing practices, participants performed one practice for three

Table A1
Effect sizes of paired comparisons among landing techniques.

	C-N vs. C-S	C-N vs. C-F	C-S vs. C-F	P-N vs. P-S	P-N vs. P-F	P-S vs. P-F
Jump Height (m)	0.31	0.27	0.01	0.05	0.24	0.34
Lateral Trunk Bending (°)	0.44	**0.84**	**1.11**	0.00	**0.93**	**0.91**
Knee Flexion Angle at Initial Contact (°)	0.40	**0.77**	**0.37**	0.28	**0.83**	**0.67**
Peak Knee Flexion Angle during Landing (°)	**0.96**	**0.45**	**0.47**	**0.74**	**0.74**	0.23
Peak Knee Abduction Angle (-) during Landing (°)	**0.61**	**0.50**	0.11	**0.31**	**0.81**	0.56
Peak Knee Internal Rotation Angle during Landing (°)	0.35	0.22	0.04	0.15	0.04	0.03
Peak Vertical GRF (BW)	**1.13**	**1.72**	**0.98**	**0.78**	**2.02**	**1.41**
Peak Knee Extension Moment (-) during Landing (BW*BH)	**0.47**	**0.90**	**0.47**	**0.28**	**0.67**	**0.38**
Peak Knee Adduction Moment during Landing (BW*BH)	0.36	0.26	0.10	0.05	**0.66**	**0.69**
Peak Knee External Rotation Moment (-) during Landing (BW*BH)	0.17	**0.57**	**0.75**	0.04	**1.00**	**1.35**

Note. C: no perturbation; P: perturbation; N: natural landing; S: soft landing; F: falling landing; GRF: ground reaction force; BW: body weight; BH: body height.

Table B1
Effect sizes of paired comparisons in variables between perturbation statuses.

	Natural Landing (C vs. P)	Soft Landing (C vs. P)	Falling Landing (C vs. P)
Jump Height (m)	0.23	0.44	0.03
Lateral Trunk Bending (°)	**1.99**	**2.31**	**1.67**
Knee Flexion Angle at Initial Contact (°)	**0.49**	**0.27**	**0.59**
Peak Knee Flexion Angle during Landing (°)	0.27	0.17	**1.04**
Peak Knee Abduction Angle (-) during Landing (°)	**1.76**	**1.37**	**0.88**
Peak Knee Internal Rotation Angle during Landing (°)	0.18	0.03	0.05
Peak Vertical GRF (BW)	**0.83**	**1.01**	0.04
Peak Knee Extension Moment (-) during Landing (BW*BH)	0.16	0.01	0.09
Peak Knee Adduction Moment during Landing (BW*BH)	**1.30**	**1.44**	**0.58**
Peak Knee External Rotation Moment (-) during Landing (BW*BH)	**0.93**	**0.84**	**0.63**

Note. C: no perturbation; P: perturbation; GRF: ground reaction force; BW: body weight; BH: body height.

landing techniques with/without perturbation.

Re-reflective markers were placed on the participant after the practice trials. Participants performed a static trial by standing straight with their feet shoulder-width apart, toes pointing forward, and arms crossed. Next, they conducted a minimum of three successful recorded trials for each combination of three landing techniques and two perturbation conditions in a randomized order. While participants were aware of the possible perturbation direction, they did not know whether a perturbation would be applied to begin with. A trial was considered successful if 1) participants performed the required landing technique, 2) participants landed with the pre-determined leg on the force platform, 3) the ball contacted the participants within a 125 ms window relative to the peak jump height, 4) the ball landed within a 1-meter circle, centered at the force platform, after contact with the participants to control the amount of contact and perturbation in mid-flight (Song et al., (2023c)). A trial was repeated if it did not meet these requirements. Participants reported whether they would predict the perturbation status before each trial at the end of the testing. They also evaluated the intensity of the perturbation compared to their experience of sports by using a 5-point scale (Song et al., (2023c)).

2.3. Data acquisition

Seventeen markers were placed on the participant's superior sternal, bilateral acromioclavicular joints and greater trochanters, and first toe, first and fifth metatarsal heads, calcaneus, medial and lateral malleolus, tibial tuberosity, inferior shank, medial and lateral femoral condyles, anterior thigh, and lateral thigh of the pre-determined landing leg (Li et al., 2020). Two markers were placed on the diameter of the slam ball to monitor the perturbation consistency. The three-dimensional coordinates of markers were captured by eight opto-reflective cameras (Vicon Motion System, Oxford, UK) at a sampling frequency of 160 Hz. Two force platforms (Bertec FP4060-10, Columbus, OH, USA) were used to collect ground reaction force, center of pressure, and free torque data at a sampling frequency of 1,600 Hz.

2.4. Data reduction

Kinematic and kinetic data were filtered by fourth-order Butterworth low-pass at 15 Hz for the inverse dynamic approach (Kristianslund et al., 2012). Kinetic data were filtered at 100 Hz to extract peak impact forces (Li et al., 2020). The hip joint center location for each side was determined as a point located between the two greater trochanters and 23.4 % of the inter-trochanter distance to the ipsilateral greater trochanter (Bennett et al., 2016). The definitions of knee and ankle joint centers, segment reference frames, and three-dimensional joint angle calculations were described in previous studies (Li et al., 2020). The knee joint resultant moments were represented as internal joint moments in the tibia reference frame using a bottom-up inverse dynamic approach (Song et al., (2023b)). GRF was normalized to body weight, and the knee joint moment was normalized to the body weight multiplying the body height.

To monitor the perturbation consistency, the middle point of the two markers placed on the slam ball was calculated. Ball contact was defined as the first frame when the horizontal ball velocity was reduced by 3 % (Song et al., (2023c)). The perturbation consistency parameters included horizontal/vertical ball velocities at ball contact, the timing offset between ball contact and peak jump height, and vertical ball contact locations (Song et al., (2023c)).

The lateral trunk bending angle at IC was calculated (Hinshaw et al., 2019). ACL loading variables were calculated by kinematic and kinetic variables at IC and early landing phase (the first 100 ms after IC) (Critchley et al., 2020). Kinematic variables assessed were knee flexion angle at IC and peak knee flexion, abduction, and internal rotation angles during early landing. Kinetic variables were calculated as peak VGRF, peak knee extension, adduction, and external rotation moments during early landing. MATLAB 2022a was used for data reduction.

2.5. Statistical analysis

One by three (landing techniques) repeated-measures analyses of variance (ANOVA) were conducted on ball contact parameters to monitor the perturbation consistency. Two (with versus without perturbation) by three (landing techniques) repeated-measures ANOVAs were performed on other variables. Paired t-tests were performed when a significant interaction effect was observed by repeated-measures ANOVAs.

In order to control the study-wide false discovery rate of 0.05, the

Benjamini-Hochberg procedure was conducted among all pairwise comparisons (Benjamini & Hochberg, 1995). Effect sizes of paired comparisons were calculated by Cohen's dz (small: ≤0.5, medium: 0.5 ~ 0.8, and large: ≥0.8) (Cohen, 1988). SPSS Statistics 22 (IBM Corporation, New York) was used.

3. Results

Seven trials (none in the same condition) were excluded from data analysis due to missing markers or the ball contacting the participant outside of the 125 ms window. Significant interactions between perturbation and landing technique were found in peak knee flexion angles, peak VGRF, and peak knee adduction moments (Table 1). The largest p-value after the Benjamini-Hochberg adjustment was 0.032 among 57 paired t-tests. The effect size for each comparison of paired t-tests is shown in the appendixes (Tables A1 and B1), including the effect of landing techniques for each perturbation condition (Appendix A1) and the effect of perturbation for each landing technique (Appendix B1).

3.1. Perturbation effects

Perturbation resulted in significantly greater lateral trunk bending angles ($p < 0.001$), knee flexion angles at IC ($P \leq 0.005$), peak knee abduction angles ($p < 0.001$), peak knee adduction moments ($p \leq 0.005$), and smaller peak knee external rotation moments ($p < 0.001$), compared to no perturbation (Table 1), regardless of landing techniques. Significantly greater peak VGRF was also observed with perturbation when participants performed natural ($p < 0.001$) and soft-landing ($p < 0.001$) conditions but not falling conditions.

3.2. Landing technique effects

The falling condition demonstrated the greatest lateral trunk bending angles ($p < 0.001$), knee flexion angle at IC ($p \leq 0.003$), and peak knee external rotation moments ($p < 0.001$), and the smallest peak knee abduction angles ($p \leq 0.003$), peak VGRF ($p < 0.001$), and peak knee extension moments ($p \leq 0.015$) compared to natural and soft landings (Table 1), regardless of perturbations. Significantly smaller peak knee adduction moments ($p \leq 0.002$) were also found for the falling condition compared to the other two conditions only when perturbation occurred.

3.3. Perturbation consistency

A significant main effect of landing techniques was reported in vertical ball velocity, with a greater downward ball velocity found for the falling condition compared to natural and soft landings (Table 2).

4. Discussion

The purpose of this study was to quantify the effect of landing techniques on variables associated with ACL loading with and without mid-flight external trunk perturbation during single-leg landings. The results generally supported the hypothesis that the mid-flight external trunk perturbation would result in greater ACL loading variables compared to no perturbation conditions. An external perturbation at the upper-trunk applied a direct force acting at a distance above the whole-body center of mass (COM). Such perturbation increased whole-body horizontal velocities and angular momentum around the COM. The external perturbation resulted in greater trunk lateral bending, greater peak VGRF, and frontal-plane knee moments when the participant had to keep their COM above their base of support (BOS). The findings were consistent with a previous study that documented increased ACL loading variables for the leg contralateral to the pushing perturbation during a double-leg landing (Song et al., (2023c)). These results also support the notion of increased risk of ACL injuries during single-leg landings with direct impact to the trunk region near the estimated time of injury (Della Villa et al., 2020; Koga et al., 2010; Olsen et al., 2004). Participants demonstrated greater knee flexion angles in perturbation conditions in the current study, associated with decreased ACL loading during landing. This was likely a compensatory strategy to mitigate the increased impact forces and frontal plane knee moments. In a riskier sports scenario, when mid-flight perturbation occurs, participants may land harder without flexing their knee prior to landing, consequently experiencing greater landing forces and knee adduction moments (Della Villa et al., 2020; Waldén et al., 2015). Such scenarios might be caused by greater perturbation, limited muscle strength, or concurrent cognitive tasks (Hughes & Dai, 2023; Song et al., 2022). In summary, the current results support the finding of increased landing impact forces and frontal-plane loading when the upper-trunk was perturbed in mid-flight. This emphasizes the need to develop effective landing strategies under such perturbation.

The findings support the hypothesis that soft landing would result in variables associated with smaller ACL loading compared to natural landing. The findings were consistent with previous studies identifying the effect of soft landing in single-leg and double-leg jump-landings without mid-flight perturbation (Li et al., 2020). Soft landing showed greater knee flexion angles, smaller VGRF, and smaller knee extension moments, associated with smaller ACL loading compared to the natural landing for both single-leg and double-leg landings. However, less protective effects of soft landing on ACL loading were shown in single-leg compared to double-leg landings. It is suggested that the modulating effect of soft landing techniques might be limited when the task is more challenging. The current findings agreed with the previous study (Li et al., 2020) that the effectiveness of soft landing was less for perturbation conditions than no-perturbation conditions, indicated by smaller effect sizes. Additionally, the soft landing did not appear to be effective in decreasing frontal plane knee moments. Therefore, more effective landing techniques might be needed to further decrease ACL loading variables under mid-flight perturbation.

The results supported the hypothesis that the falling technique would be more effective in decreasing ACL loading variables. The effect sizes between falling and other landing techniques mostly increased when perturbation was applied. Natural and soft landings required participants to maintain single-leg balance after landing. The extensive downward velocity after maximal effort jumps and lateral velocity caused by the pushing perturbation needs to be absorbed by the lower extremities in a short amount of time. In contrast, the falling technique allowed the COM to move out of the BOS and involve other body parts (hips and trunk) to decelerate the downward and lateral velocities over a longer time. Due to the removal of the constraint of the BOS, participants actively bent their trunks to the falling direction. While lateral trunk bending angle in the direction of the landing leg has been identified as a risky movement pattern for ACL injuries (Della Villa et al., 2020; Hewett et al., 2009), the current findings suggest that it might not be as risky if participants were not constrained by the landing foot and allowed themselves to fall to the ground. The findings were supported by previous studies that rolling forward showed the smallest change in the horizontal velocity during early landing compared to other landing techniques (Dai et al., 2020). Additionally, the greater downward velocities during landing could be reduced through greater knee and hip flexion (Li et al., 2020). The significantly greater peak knee flexion angle of the falling technique supported that the participants utilized a greater range of motion (ROM) in the vertical direction as the knee flexion angles at IC were similar between landing techniques in the current study. Such greater ROM allowed a lower whole-body COM position, which contributed to the lowest ACL loading experienced by the knee when falling (Li et al., 2020). Overall, when the sports environment allows, safe falling techniques appeared to be a more effective strategy to decrease ACL loading variables in both sagittal and frontal planes, particularly when the upper-trunk was perturbed, compared to soft landings.

Lastly, the external perturbation created by the slam ball was generally consistent among landing techniques with a moderate perturbation intensity. The ball contacted participants near the peak jump height at a location of approximately 39 cm above the bilateral hip positions. A slightly greater downward ball velocity was observed for the falling technique compared to natural/soft landings, which was likely due to a greater lateral trunk bending angle for the pre-planned movement pattern of the falling technique. As the participant laterally bent their trunk away from the incoming ball, the ball likely contacted the participants slightly on its downward trajectory. However, this small difference was not likely to affect the ACL loading variables. The differences in vertical velocity were around 0.1 m/s, which represented only 2 % of the horizontal velocity at 5.2 m/s. This indicates that the major effect of the perturbation remains in the horizontal direction. In addition, a downward velocity was more likely to increase the participant's peak VGRF, but the falling technique demonstrated the lowest peak VGRF. Furthermore, the subjective evaluation of the perturbation intensity was 2.7 ± 0.6, suggesting a moderate impact compared to their experience of sports (Song et al., (2023c)). None of the participants were aware of the perturbation prior to each jump. Therefore, the perturbation created was generally consistent with a moderate impact in this study.

There are several implications. The findings provide evidence to further understand the indirect contact ACL injury mechanism in ACL injury scenarios. Athletes and practitioners need to be aware of such high-risk scenarios. For instance, practitioners may instruct players to land softly, with greater knee and hip flexion and limited lateral trunk bending, to reduce ACL injury risk when perturbation occurs. Such instruction can be given through video presentations. Meanwhile, mid-flight perturbation can be incorporated into training practices by being pushed/pulled from teammates or practitioners in the air. In addition, safe and effective falling techniques are recommended to be included as a jump-landing training program for ACL injury prevention to develop subconscious compensatory strategies. Falling after landing might decrease performance under certain situations and be limited by the playing environment. For example, falling after a layup might delay a basketball player from returning to the next play. Falling on other players might cause injuries to other players. Therefore, falling training is needed to help players learn how to safely and effectively fall on the ground. Avoiding using the upper limb to support when falling and rolling to decelerate when the sports environment allows might be a compensatory strategy when landing with suboptimal controls.

Several limitations existed in this study. First, though the participants could not predict whether there would be a perturbation prior to jumps, the possible perturbation direction and location were predetermined. An unanticipated perturbation location and/or direction needs to be investigated. Second, participants have had various sports experiences, including soccer, American football, basketball, volleyball, etc. The sports experience may affect their understanding of landing techniques and expected perturbation impact. For instance, perturbation may happen more often and more aggressively in American football than in basketball. As such, it is warranted to quantify the effect of landing techniques in specific sports when a perturbation is applied. Third, the perturbation magnitude remained the same among participants. Participants who weigh less might feel the impacts more compared to participants who weigh more. Also, various perturbation magnitudes may occur during open-skill sports. For example, a greater perturbation impact can be caused by a soccer player running faster and colliding with another player than running slower. Future study needs to quantify the effect of perturbation magnitude on variables associated with ACL loading during landing. Fourth, the perturbation was applied in the medial–lateral direction, while the primary ACL loading contributors were in the sagittal plane (Beaulieu et al., 2023; Boden & Sheehan, 2022). Therefore, understanding the effect of the anterior-posterior trunk perturbation on ACL loading variables is needed.

5. Conclusion

Mid-flight external pushing perturbation on the upper trunk resulted in greater lateral trunk bending angles, peak knee abduction angles, and peak knee adduction moments during single-leg landings with different landing techniques. Soft landing increased peak knee flexion angles and decreased peak VGRF and peak knee extension moments compared to natural landing. However, the effectiveness of soft landings was limited when external perturbation was applied. Falling reduced ACL loading variables, shown by the greatest knee flexion angles and the lowest knee abduction angle, peak VGRF, and knee extension moment compared to natural and soft landings. Incorporating falling techniques into jump-landing training programs may guide players to safely fall on the ground when perturbation occurs. It provides an alternative strategy to potentially decrease indirect contact ACL injury risk when the environment allows.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Contributions.

All authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. All of the authors have read and concurs with the content in the manuscript.

Appendix A

Appendix B

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