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Original article

Indirect contact matters: Mid-flight external trunk perturbation increased unilateral anterior cruciate ligament loading variables during jump-landings

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Abstract

Background: To determine the effect of unanticipated mid-flight medial-lateral external perturbation of the upper or lower trunk on anterior cruciate ligament (ACL) loading variables during jump-landings.

Methods: Thirty-two participants performed double-leg vertical jump-landings while bilateral kinematics and kinetics were collected under 6 conditions (upper or lower trunk perturbation locations; no, left, or right perturbation directions). Two customized catapult apparatuses were created to apply pushing perturbation to participants near the maximal jump height.

Results: The ball contacted participants near the center of mass for the lower-trunk conditions and approximately 23 cm above the center of mass for the upper-trunk conditions. Under upper-trunk perturbation, the contralateral leg demonstrated significantly smaller knee flexion angles at initial contact and greater peak knee abduction angles, peak vertical ground reaction forces, peak knee extension moments, and peak knee adduction moments compared to other legs among all conditions. Under lower-trunk perturbation, the contralateral leg showed significantly smaller knee flexion angles at initial contact and increased peak vertical ground reaction forces and peak knee extension moments compared to legs in the no-perturbation conditions.

Conclusion: Mid-flight external trunk pushing perturbation increased ACL loading variables for the leg contralateral to the perturbation. The upper-trunk perturbation resulted in greater changes in ACL loading variables compared to the lower-trunk perturbation, likely due to trunk and ipsilateral leg rotation and more laterally located center of mass relative to the contralateral leg. These findings may help us understand the mechanisms of indirect-contact ACL injuries and develop jump-landing training strategies under mid-flight trunk perturbation to better prevent ACL injury.

Keywords: ACL injuries; Kinematics; Kinetics; Landing; Biomechanics

1. Introduction

The anterior cruciate ligament (ACL) injury is one of the most common and severe injuries in sports.[1,2] Video analyses of ACL injuries show that ACL injuries occur within 100 ms of initial ground contact during landing and cutting tasks.[3–7] They also show that near the time of injury the injured leg was supporting most of the body weight and the injured knee was typically close to full extension, abducted, and internally rotated.[3–7] Both *in vivo* and *in vitro* studies have shown that an anterior tibial shear force applied to an almost fully extended knee is the primary loading mechanism of the ACL, while tibial compressive forces, knee internal rotation moments, and knee abduction moments may make secondary contributions to ACL loading.[7–9]

Most ACL injuries occur without external objects directly contacting the knee joint.[6,10] As such, the mechanisms and risk factors for non-contact ACL injuries have been studied extensively.[7,11,12] However, indirect contact—defined as contact with body parts other than the injured knee[5]—appears to play a role in many ACL injuries. First, contact sports have shown more than 3 and 6 times increased risk of ACL injury

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compared to limited-contact sports and non-contact sports, respectively.[13] Additionally, video analyses of ACL injury cases in multiple team sports have shown that 8%−60% of ACL injuries are associated with contact to the trunk and/or arms prior to or near the estimated time of injury.[5] Approximately half of the ACL injuries in female team handball and netball involved certain forms of perturbation and trunk contact with external objects in the air.[14,15] One frequent scenario was when an athlete collided with something or someone or was pushed or held, consequently demonstrating unbalanced body control prior to the injury.[14−18]

Previous studies quantified the effects of mid-flight self-initiated trunk motion on jump-landing mechanics. Self-initiated trunk extension, lateral bending, and rotation could modify mid-flight whole-body and segment center of mass (COM) trajectories and result in increased unilateral ACL loading variables, such as increased ground reaction forces (GRF), decreased knee flexion angles, and increased knee abduction angles during landings.[19−21] Only a single study assessed landing mechanics by applying mid-flight lateral pulling perturbation to the upper trunk from the dominant-leg side, and it found that the perturbation resulted in increased GRF and decreased knee flexion angles for the dominant leg.[22] It should be noted that the external perturbation was only applied to the upper trunk in one direction, and only the dominant leg's landing mechanics were assessed. Quantifying the effects on bilateral landing mechanics of unanticipated mid-flight external perturbation of different locations on the trunk will provide information for understanding indirect-contact ACL injury mechanisms and help explain the connection between whole-body movements and injured knee motion in ACL injury events. A significant perturbation effect will support the inclusion of external perturbation in ACL injury risk-screening tasks, particularly for sports that have high rates of indirect-contact ACL injuries. The potential effects of external perturbation on landing mechanics may also be incorporated into educational and training programs to increase athletes' awareness and readiness to prepare for safe landings after mid-flight external perturbation.

Therefore, the purpose of this study was to determine the effects of unanticipated mid-flight medial-lateral external perturbation of the upper or lower trunk on bilateral ACL loading variables during jump-landings. It was hypothesized that the leg contralateral to the pushing perturbation would show increased ACL loading variables compared to the ipsilateral leg for both upper-trunk and lower-trunk conditions and both legs for the no-perturbation condition. In addition, upper-trunk perturbation would result in greater increases in unilateral ACL loading variables compared to lower-trunk perturbation.

2. Methods

2.1. Participants

An effect size of 0.89 was estimated for differences in peak vertical GRF between the perturbation and no-perturbation conditions.[22] Based on this effect size, a sample size of 12 was needed to achieve a power of 80% at a type I error rate of 0.05. Thirty-two recreational athletes with jump-landing experience and without a history of major injuries (16 males and 16 females, age: 21.55 ± 2.23 years (mean ± standard deviation); height: 1.72 ± 0.10 m; mass: 71.57 ± 12.88 kg) were recruited. To participate in the study, participants needed to have experience playing sports that involve jump-landing activities, such as basketball, soccer, volleyball, and American football. Participants needed to be physically active at least 2 times per week for a total of 2 h at the time of testing.[19] Participants were excluded if they (a) had a previous ACL injury or any other lower-extremity surgery, (b) had a lower-extremity injury that prevented participation in physical activities for more than 2 weeks in the last 6 months, (c) had any conditions that prevented them from maximal effort in sporting activities, (d) were allergic to adhesive, or (e) were pregnant. This study was approved by the University of Wyoming Institutional Review Board, and participants signed a consent form prior to participation.

2.2. Perturbation apparatuses

Two customized catapult apparatuses were designed to create mid-flight external perturbation with consistent lateral pushing momentum (Fig. 1). Two 4.54 kg slam balls were placed on the apparatuses with stretched elastic bands. The goal was to release the ball with constant horizontal and upward velocities and, therefore, a pre-determined projectile trajectory for a specific release height. During the jump-landing trials, researchers pulled a trigger to release the ball with the goal of having the ball contact the participant near the maximal jump height with a close-to-zero vertical ball velocity and a horizontal ball velocity of 5 m/s. To ensure the ball had close-to-full contact with the participant, the ball would need to land within a 1-m diameter circle that was drawn on the ground around the contact point. The mass and contact velocities of the ball were selected, based on preliminary testing, to result in moderate perturbation to landing patterns without significantly increasing injury risk to participants.

2.3. Protocol

After changing into spandex clothes and standard running shoes, participants performed a generalized warm-up protocol.[21] The participant's jump heights were measured using a Vertec (Sports Imports, Columbus, OH, USA). The upper-trunk and lower-trunk regions were defined between the acromion and the 5th rib and between the iliac crest and the greater trochanter, respectively. The horizontal distance of the apparatuses was adjusted based on the participants' shoulder width so that the ball would contact the participant at the ball's maximal height. Based on the participants' jump height and standing heights of the armpit and iliac crest, the release height of the ball was adjusted by moving the component that held the ball in the vertical direction so that the ball would contact the upper- or lower-trunk region when the participant reached the maximal jump height. Participants wore a helmet and performed 2 standing and 6 jump-landing practice trials to become accustomed to the perturbation. For standing trials,

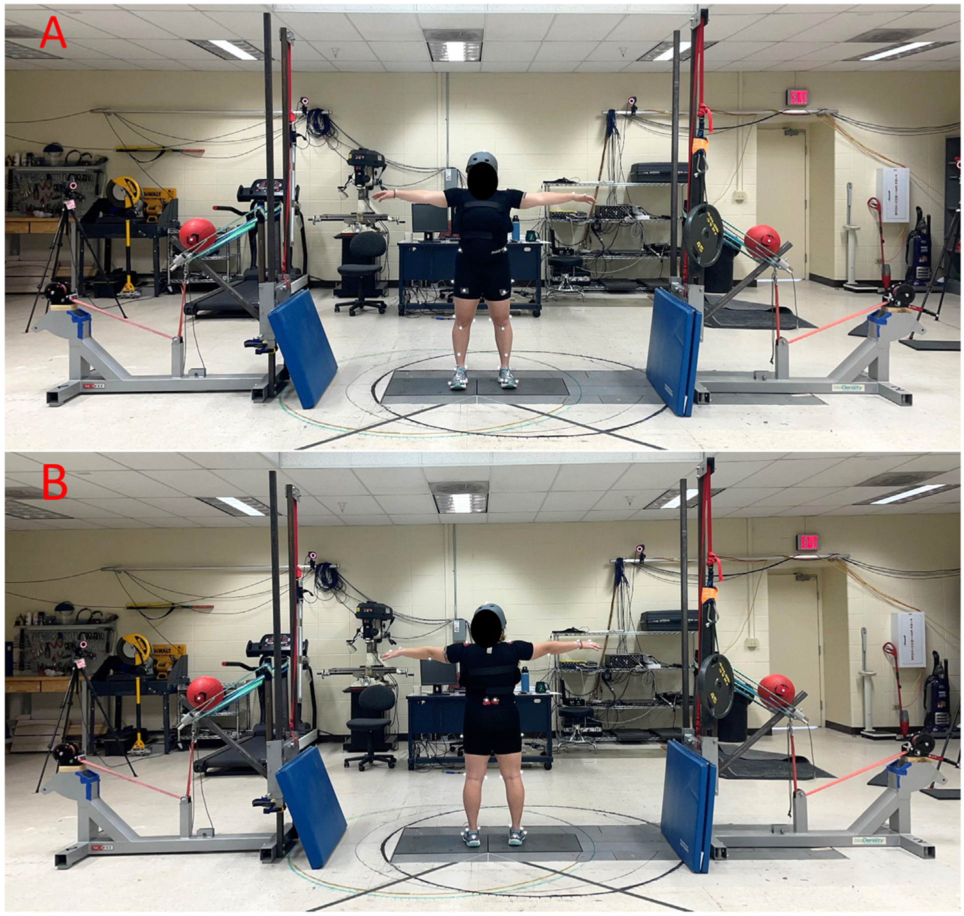

Fig. 1. This figure shows (A) anterior and (B) posterior views of marker placement and customized catapult apparatuses in a static trial.

the ball contacted the lower trunk while participants stood still. For jump-landing practice trials, participants started with feet shoulder-width apart and each foot on a force platform (Bertec FP4060-10; Bertec Corporation, Columbus, OH, USA; 1600 Hz) then jumped vertically as high as possible. Participants raised both arms during mid-flight and experienced no perturbation or left/right perturbation and landed with one foot on a force platform. No instruction regarding specific landing techniques (soft landing, trunk motion, knee flexion, *etc*.) was provided. Participants performed a combination of different perturbation locations and directions for practice trials. The current jump-landing task was designed to simulate a jump-landing with mid-flight external pushing perturbation, which could be created by pushing forces from another player or by colliding with another player or equipment. Examples of such scenarios include netball and handball players jumping to catch a ball, soccer players jumping to head a ball, and basketball players jumping to rebound a ball while there is bodily contact with another player.[14–18]

Forty retro-reflective markers were placed[19,21] on the participant (Fig. 1), and 2 markers were placed on each ball. Eight opto-reflective cameras (Bonita 10; Vicon Motion System, Oxford, UK; 160 Hz) were used to capture the 3-dimensional coordinates. After a static trial, participants performed a minimum of 3 successful trials for each combination of perturbation locations (upper or lower trunk) and perturbation directions (no, left, or right perturbation) (Fig. 2) in a randomized order. Participants knew the perturbation location but did not know the perturbation direction prior to the trial. A minimum of a 30-s break was provided between trials. A trial was repeated if (a) participants did not land with one foot on each force platform, (b) the ball contacted the participant 125 ms before or after the maximal jump height, or (c) the ball did not land in the targeted area after the impact. The check of timing offset was done by opening the motion capture software, visually inspecting the marker positions, and counting the time frames after each trial.

After completion of official trials, participants were asked whether they could predict the perturbation direction and how strongly they felt about the mid-flight perturbation via a 5-point scale (minimum (1), minor (2), moderate (3), major (4), and maximum (5)) using their sports experience as a reference.

2.4. Data reduction

Raw kinematic and GRF data were filtered using a fourth-order Butterworth low-pass filter at 15 Hz for the inverse dynamic approach.[23] Raw GRF data were also filtered at 100 Hz to extract impact GRF. Fifteen segments were defined

Fig. 2. This figure shows different mid-flight perturbation locations and directions, including (A and B) upper trunk−right perturbation, (C and D) lower trunk−left perturbation, and (E and F) lower trunk−no perturbation. The two events are (A, C, and E) the ball contacting the participant near the maximal jump height and (B, D, and F) the participant landing on the force platforms.

to calculate the whole-body COM.[21] The definitions of joint centers, segment reference frames, the calculations of knee joint angles and internal joint resultant moments, and trunk segment angles were previously described.[20] Forces were normalized to body weight. Joint moments were expressed as internal moments and normalized to the product of body weight and body height. The ball contact was defined as the first frame when the horizontal ball velocity decreased by 3%.

Variables to assess the consistency of the perturbation included horizontal and vertical ball velocities at contact, timing offset between ball contact and maximal COM height, and ball contact locations relative to COM height. ACL loading variables were quantified at initial contact and during the early-landing phase, defined as the first 100 ms after initial contact.[24] Kinematic variables included bilateral landing time differences; lateral trunk bending angles; COM−ankle absolute distances; knee flexion, knee abduction, and knee internal rotation angles at initial contact; and peak knee flexion, abduction, and internal rotation angles during early landing. Kinetic variables included peak vertical GRF and peak knee extension, external rotation, and adduction moments during early landing. Data reduction was performed in MATLAB 2021b (MathWorks, Natick, MA, USA).

2.5. Statistical analysis

Two (upper-trunk and lower-trunk perturbation locations) by 2 (left and right perturbation directions) repeated-measures analyses of variance (RMANOVA) were applied to ball velocities, contact time, and contact locations. Two (upper-trunk and lower-trunk) by 3 (no-perturbation, left-perturbation, and right-perturbation) RMANOVAs were performed for jump height, landing time differences, and lateral trunk bending angles. Two (upper-trunk and lower-trunk) by 6 (left-leg and right-leg for no-perturbation, ipsilateral-leg and contralateral-leg for left-perturbation, and ipsilateral-leg and contralateral-leg for right-perturbation) RMANOVAs were performed for other variables.

Paired t tests were utilized between each pair of comparisons when a significant main effect was found by RMANOVAs. A type-I error of RMANOVAs was set at 0.05. The Benjamini−Hochberg procedure was performed on all t tests to control the study-wide false discovery rate at 0.05.[25] The effect sizes were evaluated using Cohen's dz. Effect size ≤0.5 is defined as "small," 0.5−0.8 is "medium," or ≥0.8 is "large."[26] Statistical analyses were conducted in SPSS statistics (Version 22.0; IBM, Armonk, NY, USA).

3. Results

No injury occurred, and no participant reported that they could predict the perturbation direction. The subjective assessments of the perturbation were 2.6 ± 0.7, indicating a close-to-moderate perturbation. Seven trials (none in the same condition) were excluded due to the ball contacting participants out of the 125 ms range or missing markers. The largest p value for paired t tests was 0.031 after the false discovery adjustment. The effect sizes and p values for each comparison were included in the Supplementary Tables 1−4.

3.1. Perturbation consistency

Horizontal ball velocities at contact were slightly (2%) but significantly faster for the lower-trunk conditions than the upper-trunk conditions for both left and right perturbations (Table 1). Contact locations were significantly higher for the upper-trunk conditions compared to the lower-trunk conditions for both left and right perturbations. No significant differences were observed for vertical ball velocities or contact time.

3.2. Perturbation effects

Significant interactions were found for all variables except jump height and peak knee internal rotation angle (Tables 2−4). Left and right perturbation generally resulted in similar changes in ACL loading variables to the ipsilateral and contralateral legs compared to no-perturbation for both upper-trunk and lower-trunk conditions. The upper-trunk perturbation resulted in the greatest landing-time difference, with the contralateral leg landing earlier than the ipsilateral leg, and the greatest lateral trunk bending to the contralateral leg when compared to other conditions. The upper-trunk perturbation also showed the shortest COM−ankle distance for the contralateral leg and the greatest COM−ankle distance for the ipsilateral leg.

Regarding ACL loading variables, the contralateral leg for the upper-trunk perturbation demonstrated the smallest knee flexion and the greatest knee abduction angles at initial contact and the greatest peak knee abduction angles, peak vertical GRF, peak knee extension moments, and peak knee adduction moments compared to other legs among all conditions. The contralateral leg for the lower-trunk perturbation also showed decreased knee flexion angle at initial contact and increased peak vertical GRF and knee extension moment compared to the 2 legs in the no-perturbation conditions.

A secondary analysis was performed with sex as a between-participant variable. While males and females demonstrated significant differences for several variables, their responses to perturbation locations and directions were similar overall (Supplementary Tables 5−7).

4. Discussion

The purpose of this study was to determine the effects of unanticipated mid-flight medial-lateral external perturbation of the upper or lower trunk on bilateral ACL loading variables

Table 1
RMANOVAs for ball contact parameters (mean ± standard deviation).

	Left perturbation	Right perturbation	p for RMANOVA		
			Location	Direction	Interaction
Horizontal ball velocity (m/s)					
Upper trunk	5.05 ± 0.30*	5.06 ± 0.27*	<0.001	0.807	0.020
Lower trunk	5.18 ± 0.24*	5.14 ± 0.24*			
Vertical ball velocity (m/s)					
Upper trunk	−0.05 ± 0.29	−0.00 ± 0.33	0.207	0.499	0.662
Lower trunk	−0.03 ± 0.26	0.01 ± 0.27			
Timing offset (ms)					
Upper trunk	6.0 ± 30.4	−0.9 ± 42.5	0.183	0.681	0.393
Lower trunk	8.0 ± 37.5	9.0 ± 33.1			
Contact location (m)					
Upper trunk	0.22 ± 0.07*	0.24 ± 0.06*	<0.001	0.169	0.943
Lower trunk	−0.04 ± 0.07*	−0.02 ± 0.07*			

Notes: Timing offset was defined as the time differences between ball contact and maximal COM height, with a positive number indicating the ball contacted earlier than the maximal COM height. Contact locations were defined as the differences between the ball and the COM, with a positive number indicating the ball was higher than the COM.

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* Significantly different between upper and lower trunks for both perturbation directions.Abbreviations: COM = center of mass; RMANOVA = repeated-measures analyses of variance.

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Table 2
RMANOVAs for jump height, landing time differences, and lateral trunk bending angles (mean ± standard deviation).

	No perturbation	Left perturbation	Right perturbation	*p* values for RMANOVAs		
				Location	Direction	Interaction
Jump height (m)						
Upper trunk	0.44 ± 0.11	0.44 ± 0.11	0.44 ± 0.11	0.138	0.709	0.268
Lower trunk	0.44 ± 0.11	0.44 ± 0.11	0.44 ± 0.11			
Landing time differences (ms)						
Upper trunk	0.1 ± 6.0	38.0 ± 77.0[*,†]	30.6 ± 25.2[*,†]	0.002	0.003	0.023
Lower trunk	1.0 ± 7.4	6.7 ± 10.2[*,†]	7.9 ± 11.5[*,†]			
Lateral trunk bending angles at initial contact (°)						
Upper trunk	−0.4 ± 2.3	6.4 ± 3.0[*,†]	6.8 ± 3.4[*,†]	<0.001	<0.001	<0.001
Lower trunk	−0.2 ± 2.9	−3.4 ± 3.8[*,†]	−1.8 ± 3.3[*,‡]			

Notes: Landing time differences were defined as the time differences at initial ground contact between 2 legs, with a positive number indicating the contralateral leg or the right leg landed earlier with or without perturbation. Lateral trunk bending angles were positive when the trunk bent to the contralateral or the right side with or without perturbation.

* Significantly different compared with lower trunk for each perturbation direction.

† Significantly different compared with no perturbation for each perturbation location.

‡ Significantly different compared with left perturbation for each perturbation location.Abbreviations: RMANOVA = repeated-measures analyses of variance.

Table 3
RMANOVAs for landing kinematic variables (mean ± standard deviation).

	No perturbation		Left perturbation		Right perturbation		*p* for RMANOVA		
	Left leg	Right leg	Ipsilateral leg	Contralateral leg	Ipsilateral leg	Contralateral leg	Location	Direction-leg	Interaction
COM-ankle distance at initial contact (m)									
Upper trunk	0.18 ± 0.03[b]	0.18 ± 0.03[b]	0.27 ± 0.05[a,*]	0.16 ± 0.03[c,*]	0.28 ± 0.04[a,*]	0.16 ± 0.03[c,*]	<0.001	<0.001	<0.001
Lower trunk	0.19 ± 0.03[b,c]	0.17 ± 0.03[c]	0.21 ± 0.03[a,*]	0.19 ± 0.03[b,*]	0.21 ± 0.03[a,*]	0.18 ± 0.03[b,c,*]			
Knee flexion angle at initial contact (°)									
Upper trunk	15.2 ± 5.9[b]	15.2 ± 6.6[b]	20.7 ± 9.4[a,*]	12.2 ± 5.9[c,*]	22.7 ± 13.0[a,*]	12.6 ± 4.6[c,*]	0.006	<0.001	<0.001
Lower trunk	16.0 ± 5.8[a]	15.2 ± 6.2[a,b]	16.0 ± 6.4[a,*]	13.3 ± 5.8[c,*]	16.3 ± 8.3[a,b,*]	14.1 ± 5.1[b,c,*]			
Knee abduction angle (−) at initial contact (°)									
Upper trunk	0.7 ± 2.3[c]	−0.4 ± 1.8[b]	2.5 ± 2.6[d,*]	−2.3 ± 1.7[a,*]	1.7 ± 3.5[c,d,*]	−1.5 ± 2.1[a,*]	0.041	<0.001	<0.001
Lower trunk	0.9 ± 2.4[d]	−0.3 ± 2.0[b,c]	0.6 ± 2.5[c,d,*]	−1.0 ±1.7[a,*]	−0.6 ± 1.9[a,b,*]	−0.3 ± 2.1[a,b,*]			
Knee internal rotation angle at initial contact (°)									
Upper trunk	−0.9 ± 4.7[b,c]	−1.8 ± 4.5[c]	2.9 ± 6.6[a]	−0.5 ± 4.7[b,*]	2.6 ± 6.0[a]	−1.2 ± 4.9[b,c]	0.037	0.002	0.040
Lower trunk	−0.9 ± 4.2[b,c,d]	−0.9 ± 5.6[c]	2.0 ± 4.2[a]	−2.8 ± 5.3[d,*]	1.1 ± 5.6[a,b]	−1.9 ± 4.8[c,d]			
Peak knee flexion angle during early landing (°)									
Upper trunk	61.6 ± 10.3[a]	61.2 ± 10.4[a,b]	53.2 ± 13.2[e,*]	57.7 ± 8.3[c,d]	55.1 ± 12.9[d,e]	59.3 ± 8.1[b,c,*]	0.106	<0.001	<0.001
Lower trunk	62.0 ± 11.0[a]	62.0 ± 10.1[a]	58.0 ± 10.2[b,*]	57.5 ± 10.6[b]	56.6 ± 10.4[b]	57.4 ± 9.7[b,*]			
Peak knee abduction angle (−) during early landing (°)									
Upper trunk	0.5 ± 2.4[c]	−1.0 ± 2.4[b]	2.0 ± 2.8[d,*]	−2.9 ± 2.3[a,*]	0.2 ± 3.8[c,*]	−1.7 ± 2.4[b,*]	0.064	<0.001	<0.001
Lower trunk	0.6 ± 2.7[d]	−1.0 ± 2.7[b,c]	−0.2 ± 3.1[b,c,*]	−1.3 ± 2.0[b,*]	−2.1 ± 2.8[a,*]	−0.4 ± 2.3[b,c,*]			
Peak knee internal rotation angle during early landing (°)									
Upper trunk	6.7 ± 4.6	5.6 ± 4.8	7.7 ± 5.7	7.5 ± 5.1	7.5 ± 6.2	7.5 ± 5.1	0.426	0.559	0.091
Lower trunk	6.3 ± 4.3	7.0 ± 5.5	6.8 ± 4.5	7.4 ± 5.6	6.0 ± 5.1	7.3 ± 5.0			

Notes: COM−ankle distance was defined as the absolute distance between the whole-body COM and each ankle center in the medial-lateral direction. − means knee abduction angles were negative based on the way we defined the direction of 3D joint angles.

[a] Was the greatest.

[b] Was the second greatest.

[c] Was the third greatest.

[d] Was the fourth greatest.

[e] Was the least among 6 combinations between perturbation directions and landing legs for each perturbation location. The conditions with the same letter were not significantly different from one another.

* Significantly different between upper and lower trunks for each combination between perturbation directions and landing legs.Abbreviations: COM = center of mass; RMANOVA = repeated-measures analyses of variance.

during jump -landings. The ball parameters were consistent, with only minimal differences in horizontal ball velocity between the upper-trunk and lower-trunk conditions, likely due to the inherent variation of the apparatuses. It is unlikely this difference affected the results since the upper-trunk condition, which demonstrated the greatest ACL loading variables, exhibited slightly lower horizontal ball velocities. On average, the ball contacted the participant near the maximal jump height with close-to-zero vertical ball velocity. Ball contact locations were near the COM (−3 ± 7 cm) in the vertical direction for the lower-trunk conditions and approximately 23 ± 7 cm above the COM for the upper-trunk conditions.

Table 4
RMANOVAs for landing kinetic variables (mean ± standard deviation).

	No perturbation		Left perturbation		Right perturbation		p for RMANOVA		
	Left leg	Right leg	Ipsilateral leg	Contralateral leg	Ipsilateral leg	Contralateral leg	Location	Direction-leg	Interaction
Peak vertical GRF during early landing (BW)									
Upper trunk	2.5 ± 0.7^{b}	2.4 ± 0.6^{b}	$1.4 \pm 0.7^{c,*}$	$3.7 \pm 0.6^{a,*}$	$1.4 \pm 0.5^{c,*}$	$3.7 \pm 0.7^{a,*}$	0.295	<0.001	<0.001
Lower trunk	2.3 ± 0.7^{b}	2.5 ± 0.6^{b}	$2.0 \pm 0.9^{c,*}$	$3.2 \pm 0.7^{a,*}$	$2.1 \pm 0.8^{c,*}$	$3.2 \pm 0.7^{a,*}$			
Peak knee extension moment (−) during early landing (BW × BH)									
Upper trunk	-0.09 ± 0.02^{c}	-0.10 ± 0.02^{b}	$-0.04 \pm 0.03^{d,*}$	-0.13 ± 0.03^{a}	$-0.04 \pm 0.02^{d,*}$	-0.13 ± 0.03^{a}	0.005	<0.001	<0.001
Lower trunk	-0.09 ± 0.02^{d}	-0.10 ± 0.03^{c}	$-0.05 \pm 0.02^{e,*}$	-0.13 ± 0.03^{a}	$-0.06 \pm 0.02^{e,*}$	-0.12 ± 0.03^{b}			
Peak knee adduction moment during early landing (BW × BH)									
Upper trunk	0.017 ± 0.010^{c}	$0.021 \pm 0.013^{b,c}$	$0.019 \pm 0.010^{b,c,*}$	$0.035 \pm 0.015^{a,*}$	$0.022 \pm 0.010^{b,*}$	$0.033 \pm 0.014^{a,*}$	0.539	<0.001	<0.001
Lower trunk	0.020 ± 0.013^{b}	0.019 ± 0.014^{b}	$0.036 \pm 0.015^{a,*}$	$0.020 \pm 0.013^{b,*}$	$0.037 \pm 0.014^{a,*}$	$0.019 \pm 0.013^{b,*}$			
Peak knee external rotation moment (−) during early landing (BW × BH)									
Upper trunk	$-0.006 \pm 0.004^{a,b,*}$	-0.003 ± 0.004^{c}	$-0.005 \pm 0.005^{b,c,*}$	$-0.003 \pm 0.003^{c,*}$	$-0.004 \pm 0.003^{c,*}$	$-0.006 \pm 0.004^{a,b,*}$	0.742	<0.001	<0.001
Lower trunk	$-0.004 \pm 0.004^{c,*}$	-0.004 ± 0.003^{c}	$-0.002 \pm 0.002^{d,*}$	$-0.007 \pm 0.006^{b,*}$	$-0.002 \pm 0.002^{d,*}$	$-0.009 \pm 0.005^{a,*}$			

Note: − means knee abduction angles were negative based on the way we defined the direction of 3D joint angles.
[a] Was the greatest
[b] Was the second greatest
[c] Was the third greatest
[d] Was the fourth greatest.
[e] Was the least among 6 combinations between perturbation directions and landing legs for each perturbation location. The conditions with the same letter were not significantly different from each other.
* means significantly different between upper and lower trunks for each combination between perturbation directions and landing legs.Abbreviations: BH = body height; BW = body weight; GRF = ground reaction force; RMANOVA = repeated-measures analyses of variance.

4.1. Perturbation vs. no-perturbation

The findings supported the hypothesis that mid-flight external perturbation would result in increased ACL loading variables for the leg contralateral to the pushing perturbation compared to the ipsilateral leg and both legs in the no-perturbation conditions. Both upper-trunk and lower-trunk perturbation demonstrated smaller knee flexion angles at initial contact, increased peak vertical GRF, and increased knee extension moments for the contralateral leg compared to the ipsilateral leg and both legs in the no-perturbation conditions. Video analyses of ACL injuries have shown that contact with the trunk and arms comprises more than 80% of indirect contact near the time of ACL injuries in team sports, such as soccer, handball, and basketball.[6,14,17,18] Trunk contact prior to landing might increase lateral trunk bending and apply forces to the athlete, consequently resulting in increased knee loading and sub-optimal knee controls.[5] The increased unilateral ACL loading variables in the current study are in line with previous video observations of trunk perturbation in many ACL injury events[4,14,17,18,27] and support the theory that indirect contact can result in asymmetrical landing patterns and elevated injury risk for one leg.

In addition, Yom et al.[22] reported that the mid-flight lateral pulling perturbation of the upper trunk resulted in decreased knee flexion angles, increased GRF, and increased knee moments for the dominant leg (ipsilateral leg). From a mechanical perspective, a lateral pulling force on one side of the trunk has the same effect on the COM trajectory and whole-body rotation as a lateral pushing force on the other side. Therefore, the findings of increased ACL loading variables for the contralateral leg associated with pushing perturbation were consistent with increased ACL loading variables for the ipsilateral leg associated with pulling perturbation in the previous study.[22] The current study utilized the pushing mechanism, as it is more likely to occur in real-life sports situations than the pulling mechanism because a collision between athletes results in a pushing perturbation. Both external pushing and pulling forces could increase the whole-body lateral velocity prior to landing. A study showed that individuals preferred to use the lateral leg to decelerate the horizontal velocity of the COM during a lateral jump landing, potentially due to stronger hip abductors than hip adductors.[20] As such, the mechanical consequence of an increased horizontal velocity, along with the preference for one leg in the lateral landing, was likely a cause of the increased unilateral ACL loading variables for both trunk perturbation locations in this study.

4.2. Upper-trunk vs. lower-trunk perturbation

The findings also support the hypothesis that the upper-trunk perturbation would result in greater increases in unilateral ACL loading variables compared to the lower-trunk perturbation. In addition to the increased horizontal ball velocity, the external perturbation could also increase the whole-body angular momentum when the pushing force was acting away from the COM. For the lower-trunk perturbation conditions, as the perturbation was applied close to the COM, the perturbation effect was mainly related to the horizontal velocity of the COM. Due to a lack of changes in rotation, there was no significant trunk bending towards the contralateral leg. Furthermore, the COM had a similar distance to each ankle, and the landing time differences at initial contact were small for the lower-trunk perturbation conditions.

On the other hand, the perturbation was applied superior to the COM for the upper-trunk perturbation conditions, causing whole-body angular momentum in the frontal plane to rotate towards the contralateral side.[5] Participants, therefore, mostly rotated the trunk and the ipsilateral leg as a function of the increased angular momentum. Consequently, trunk bending angles were greater, and the COM was located much closer to the contralateral leg in the medial-lateral direction at initial ground contact. Also, the ipsilateral leg was likely placed further away from the ground in the vertical direction due to its rotation compared to the contralateral leg. This asymmetrical landing posture at initial ground contact subsequently resulted in greater landing time differences, with the contralateral leg demonstrating the smallest knee flexion and greatest knee abduction angles compared to other conditions. While increasing ACL loading variables for the contralateral leg, this asymmetric landing pattern allowed participants to land with the leg that had a short moment arm between the point of GRF application and the COM, making it less likely they would fall laterally to the ground. For several participants' upper-trunk perturbation trials, the landing time differences were so significant that they almost demonstrated a single-leg landing, as the ipsilateral leg was still lifted from the ground when the contralateral leg landed. A previous study found that self-initiated lateral trunk bending resulted in the upper-body COM moving to the bending direction while the lower-body COM shifted to the opposite direction, leading the leg in the trunk bending direction to land earlier and experience greater loading.[21] The current findings are consistent with those of this previous study and suggest that asymmetric landing postures at initial ground contact could increase unilateral ACL loading during early landing. Despite being instructed to land with both legs, performance demands such as self-initiated trunk motion and external trunk perturbation could have caused individuals to land mostly on a single leg.

In addition to the greatest loading in the sagittal plane, the contralateral leg in the upper-trunk conditions also demonstrated the greatest knee abduction angles and internal knee adduction moments, which were not observed for the lower-trunk conditions. Previous studies have suggested that limited knee flexion, greater impact GRF, and greater external knee abduction moments all contribute to greater ACL loadings.[7,8,28,29] The increased frontal-plane loading was likely due to increased lateral movement of the whole-body COM relative to the contralateral knee, creating an external knee abduction moment to move the knee into a more abducted position. These findings of increased knee abduction angles and internal knee adduction moments as a function of a more laterally placed whole-body COM were consistent with previous findings related to self-initiated trunk motion.[21] The findings were also in line with video analyses showing that the trunk was more likely to bend toward the injured leg when ACL injuries occurred.[5]

4.3. Clinical implications

First, the findings may help us better understand the mechanisms of indirect-contact ACL injuries. Indirect contact does not apply a force to directly rupture the ACL, but it can increase ACL loading and injury risk by changing landing postures and loading distributions among segments and joints. Indirect contact not only applies an external force to the athlete, but can change an athlete's movement velocities, joint angles, whole-body rotation, whole-body COM and segment COM distribution, and self-selected strategies for landing under the constraints of their specific sports environment. While more studies have begun documenting indirect contact as a key characteristic of ACL injuries, future video-analysis studies are encouraged to provide more information, such as the estimated magnitudes, time, and location of the perturbation, as well as its potential effect on whole-body motion during ACL injuries.

Second, the current ACL injury risk screening generally uses pre-planned and controlled double-leg or single-leg tasks to assess landing biomechanics. Future studies might consider incorporating jump-landing tasks with external perturbation to better simulate single-leg landing patterns imposed by sports performance, particularly for sports that have a high injury rate of indirect-contact ACL injuries. For instance, athletes' lateral trunk bending angles, bilateral landing time differences, and knee flexion may be practically assessed during catching and passing ball maneuvers while external pulling or pushing perturbation is applied to the athlete's upper trunk by a coach or trainer. For research studies, similar dynamic screening tasks with external perturbation and close-to-play sports scenarios may be considered for improving the limited ACL injury screening tools.[30−32]

Third, athletes and practitioners need to be aware of the increased unilateral ACL loading associated with external perturbation, particularly on the upper trunk. To promote athletes' awareness of how mid-flight external pushing or pulling perturbation might increase knee loading for a specific leg, educational videos can be made to explain the mechanical connection between trunk perturbation and landing mechanics. Practically, athletes could perform sports-specific jump-landing tasks with unanticipated trunk perturbation provided manually or through a resistance band by teammates or coaches.[33] Athletes should be encouraged to land softly with increased knee flexion angles if the mid-flight external perturbation results in one-leg landing much earlier than the other leg. When the sports environment allows, athletes may be trained to decrease ACL loading variables by using safe and effective falling strategies that increase the joint range of motion and utilize other parts of the body, as well as eliminate the constraint between the COM and base of support.[24] New educational and training strategies may help athletes better prepare for high-risk scenarios with significant external trunk perturbation in sports competitions.

4.4. Limitations

First, the perturbation was limited to a single magnitude in the frontal plane. Participants with lower body weight might experience greater perturbation compared to those with greater body weight. Participants with different sports backgrounds might also interpret the magnitude of the perturbations differently. Future studies could consider varying the perturbation

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magnitudes and including perturbation in other planes. Second, participants knew the perturbation location prior to the jump-landing task; this could be incorporated as an unanticipated factor in the future. Third, the current study only included jump-landing tasks. The effect of trunk perturbation on cutting and other direction-changing task mechanics warrants further investigation. Fourth, participants were constrained to land bilaterally with each foot on a force platform. A larger data collection area with more force platforms may allow participants to utilize landing techniques more similar to those they perform in real sports situations. Last, participants utilized their self-selected landing techniques in all jump-landing conditions. A worthy investigation would be to evaluate how different landing techniques might help reduce the elevated ACL loading variables associated with mid-flight trunk perturbation.

5. Conclusion

Mid-flight external pushing perturbation of the upper and lower trunk resulted in increased ACL loading variables for the leg contralateral to the pushing perturbation. The increased COM horizontal velocity likely contributed to increased knee extension moment for both upper-trunk and lower-trunk conditions. The upper-trunk perturbation further resulted in greater increases in unilateral ACL loading variables, with decreased knee flexion angle at initial contact, increased knee abduction angle at initial contact, increased peak knee abduction angle, and increased peak knee extension and adduction moments compared to the lower-trunk perturbation. The upper-trunk perturbation resulted in greater changes in ACL loading variables compared to the lower-trunk perturbation, likely due to the trunk and ipsilateral leg rotation imposed by the increased whole-body angular momentum and the more laterally located COM relative to the contralateral leg. These findings may help us better understand the mechanisms of indirect-contact ACL injuries and develop effective jump-landing screening and training strategies under mid-flight trunk perturbation to prevent ACL injury.

Table 3

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Authors' contributions

YS participated in the design of the study and development of apparatuses, contributed to data collection, data reduction/analysis, and interpretation of results; LL, RF, and MJ contributed to data collection; JL participated in the design of the study and development of apparatuses; GH, DS, MW, and QZ participated in the design of the study; BD participated in the design of the study, contributed to data collection, data reduction, and interpretation of results. All authors contributed to the manuscript writing. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jshs.2022.12.005.

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