TRUNK POSTERIOR PULLING PERTURBATION INCREASED VARIABLES ASSOCIATED WITH ACL LOADING DURING LANDING

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The purpose of this study was to identify the effects of posterior pulling perturbation applied to the upper or lower trunk on variables associated with anterior cruciate ligament (ACL) loading during landing. Thirty-eight participants performed double-leg vertical jumps with and without posterior pulling perturbation applied to the upper/lower trunk shortly after the peak jump height. Perturbation resulted in significantly greater impact forces, smaller knee flexion angles, and greater knee extension and adduction moments compared to no perturbation. Upper trunk perturbation resulted in smaller trunk flexion angles than the lower trunk perturbation location. Mid-flight posterior pulling perturbation applied to upper and lower trunks increased ACL loading variables during landing. Posterior pulling perturbation or anterior pushing perturbation might be involved in training to decrease ACL injury risk.

KEYWORDS: anterior cruciate ligament injury, biomechanics, kinematics, kinetics, knee

INTRODUCTION: An injury to the anterior cruciate ligament (ACL) typically occurs shortly after initial ground contact (IC) during landing (Dai et al., 2015; Song et al., 2023), characterized as the injured leg experiencing a high ground reaction force (GRF) with the knee in a near-fully extended, abducted, and internally rotated position (Boden et al., 2022). Although most ACL injuries happen without external objects directly contacting the knee joint, contact with other body parts except for the injured knee appears to contribute to an average of 34% of ACL injuries (Song et al., 2023). One of the frequent ACL injury scenarios was a player being collided, pushed, or held and consequently demonstrating suboptimal body control during mid-flight prior to the estimated injury time (Stuelcken et al., 2016; Sheehan et al., 2012).
Previous studies quantified the effects of mid-flight medial-lateral external trunk perturbation on jump-landing mechanics (Yom et al., 2014; Song et al., 2023). Mid-flight external medial-lateral pushing perturbation increased peak vertical GRF and knee extension and adduction moments, as well as decreased knee flexion angles for the leg contralateral to the perturbation direction (Song et al., 2023). Furthermore, upper trunk perturbation resulted in a greater increase in these variables compared to the lower trunk perturbation locations, associated with increased ACL injury risk during landing (Song et al., 2023). While the biomechanical connections between medial-lateral trunk perturbation and landings have been quantified, the effect of trunk perturbation and perturbation location in the sagittal plane on landing mechanics is unknown. In fact, the primary ACL loading mechanism is the anterior tibial shear force applied to an almost fully extended knee, aligning with the main function of ACL is to restrict the tibia moving forward relative to the femur (Boden et al., 2022; Dai et al., 2015). In addition, video analysis reported that limited trunk flexion angles and greater anterior-posterior distance between the center of mass (COM) and base of support were associated with increased ACL injury risk (Song et al., 2023; Sheehan et al., 2012). As such, it is critical to understand the effect of mid-flight external trunk perturbation in the sagittal plane, particularly posterior perturbation, which is likely to restrict trunk flexion and frequently happens in team sports (an opponent grabs another player's trunk to halt or catch them during games and an opponent pushing another player in the front), on variables associated with ACL loading during landing.
The current study aimed to quantify the effect of mid-flight posterior pulling perturbation applied to the upper trunk or lower trunk on lower limb landing mechanics. It was hypothesized that the perturbation would result in variables associated with increased ACL loading during landing compared to no perturbation. Additionally, the upper trunk perturbation location would result in a greater increase in ACL loading variables compared to the lower trunk perturbation location.

METHODS: Thirty-eight participants were recruited in this study (19 females and 19 males, age: 22.8 ± 3.0 years; body height: 172.5 ± 7.4 cm, body weight: 72.5 ± 11.3 kg). The smallest effect size in peak vertical GRF and peak knee extension moment between upper and lower trunk perturbation locations was 0.55 (Song et al., 2023). A sample size of 28 was needed to achieve a power of 80% at a type I error rate of 0.05. The inclusion and exclusion criteria were reported previously (Song et al., 2023). The current study was approved by XXX Institutional Review Board, and participants signed a consent prior to testing.
One customized device was designed to create mid-flight external perturbation with consistent pulling momentum (Song et al., 2023). One 4.54 kg slam ball was hung on the device and connected with the participants through a strap (Figure 1). Researchers released a trigger, allowing the ball to drop freely. The goal was to pull participants posteriorly from the dropping ball near the peak jump height via the strap at the upper or lower trunk. The strap did not restrict the movement while jumping. Standing and conditional practice trials were performed to become accustomed to the perturbation. For the standing practice, participants stood still with the perturbation, pulling them posteriorly. For the conditional practices (Figure 1), participants started with feet shoulder-width apart and each foot on one force plate (Bertec, FP4060, USA, 1600 Hz), then jumped vertically for height. Participants focused on touching a basketball hanging above their standing position at the peak jump height. Overall, four practices were performed under a combination of perturbation location (upper trunk vs. lower trunk) and status (perturbation vs. no perturbation). Thirty-six reflective markers were placed on the participant, and two markers were placed on the ball. Eight opto-reflective cameras (Vicon Bonita 10, UK, 160Hz) were used to capture the coordinates of markers. A minimum of three successful trials for each condition were performed in a randomized order (Figure 1). Participants knew the perturbation location but did not know the perturbation status prior to each trial.

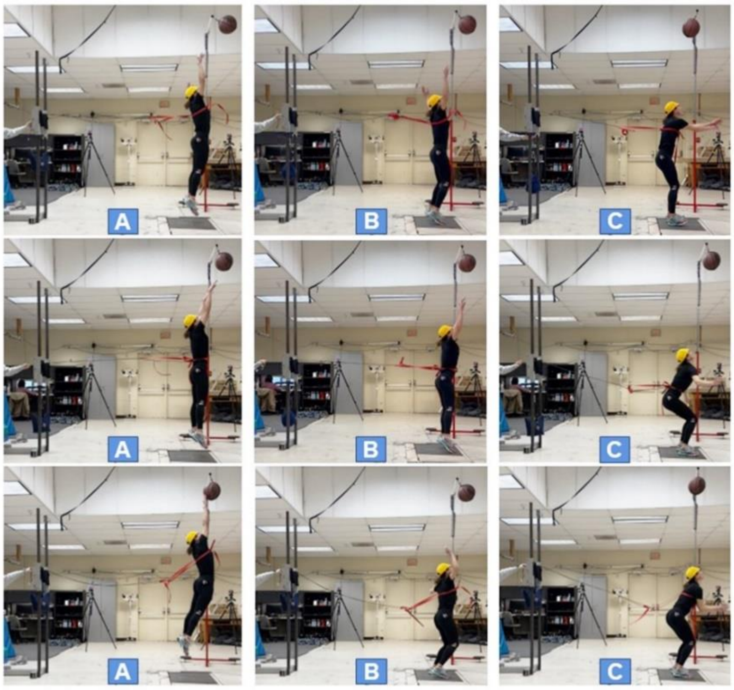

Figure 1: Upper trunk (top row), lower trunk (middle row), and no perturbation (bottom row) during mid-flight (column A), at initial ground contact (column B), and landing (column C).

Time offset (perturbation time relative to peak jump height with a positive number indicating the pulling perturbation occurred later than the peak jump height) was calculated to monitor the perturbation, which was designed to be within 150ms near the peak jump height to control the perturbation consistency. The dependent variables included jump height, trunk flexion angle and knee flexion angle at IC, peak trunk flexion angle, peak knee flexion, abduction, and internal rotation angles during landing (100ms after IC), peak vertical GRF and peak knee extension, adduction, and external rotation moments during landing. Knee angles, moments, and vertical GRF were reported as average between both legs. Data reduction was conducted in MATLAB 2022b, and detailed data processing was previously described (Song et al., 2023). Two-by-two repeated-measure ANOVAs were applied to identify the effect of perturbation locations and statuses. Paired t-tests were conducted following a significant main effect ($p \le 0.05$) observed by ANOVAs. The significant alpha rate was defined as 0.05.

RESULTS: Data from eight participants (5 males and 3 females) were excluded from analyses due to missing trials for one condition (perturbation occurred outside of the 150ms window relative to the peak jump height or missing markers). Participants demonstrated consistent jump height (Table 1). There were no significant differences in time offset between perturbation locations (Upper trunk: 87.8 ± 38.9ms; Lower trunk: 80.9 ± 40.7ms; p=0.415).
In terms of the perturbation effects, perturbation resulted in significantly greater peak vertical GRF (p=0.045), knee flexion angles at IC (p=0.006), peak knee abduction angles (p=0.027), and peak knee extension and adduction moments (p<0.001), as well as smaller peak knee flexion angles (p=0.002), regardless of perturbation locations (Table 1). Additionally, smaller trunk flexion angles at IC (p=0.006) and peak trunk flexion angles (p<0.001) were found in the upper trunk perturbation location compared to no perturbation condition. In terms of the effects of perturbation locations, upper trunk perturbation location resulted in smaller trunk flexion angles at IC (p=0.006) and peak trunk flexion angles (p<0.001) compared to lower trunk perturbation location when perturbation was applied (Table 1).

Table 1: Means ± standard deviations for dependent variables and effect sizes between perturbation and no perturbation at upper trunk (UT) and lower trunk (LT) locations.

		Perturbation	No Perturbation	Effect Size
Jump Height (m)	UT	0.44 ± 0.11	0.44 ± 0.11	--
	LT	0.44 ± 0.11	0.44 ± 0.11	--
Trunk Flexion Angle at Initial	UT	2.20 ± 6.68^*	4.70 ± 5.25*	0.54
Contact (°)	LT	4.49 ± 5.47^	4.24 ± 5.28	--
Peak Trunk Flexion Angle during	UT	6.78 ± 8.64^*	11.48 ± 7.39*	0.84
Landing (°)	LT	10.66 ± 7.45^	11.48 ± 7.57	--
Peak Vertical Ground Reaction	UT	2.23 ± 0.63*	2.21 ± 0.68*	0.28
Force during Landing (BW)	LT	2.30 ± 0.59*	2.16 ± 0.59*	0.28
Knee Flexion Angle at Initial	UT	13.91 ± 5.07*	13.35 ± 4.80*	0.39
Contact (°)	LT	13.49 ± 4.76*	12.03 ± 3.82*	0.39
Peak Knee Flexion Angle during	UT	53.47 ± 9.32*	55.19 ± 8.54*	0.45
Landing (°)	LT	52.60 ± 9.11*	54.09 ± 8.4*	0.45
Peak Knee Abduction Angle during	UT	-2.12 ± 2.65*	-1.87 ± 2.49*	0.32
Landing (°)	LT	-2.10 ± 2.45*	-1.85 ± 2.55*	0.32
Peak Knee Internal Rotation Angle	UT	5.53 ± 4.33	5.98 ± 3.86	--
during Landing (°)	LT	5.94 ± 3.24	5.44 ± 3.35	--
Peak Knee Extension Moment	UT	-0.093 ± 0.024*	-0.083 ± 0.020*	0.84
during Landing (BW* BH)	LT	-0.089 ± 0.023*	-0.081 ± 0.021*	0.84
Peak Knee Adduction Moment	UT	0.024 ± 0.010*	0.022 ± 0.010*	0.59
during Landing (BW* BH)	LT	0.024 ± 0.009*	0.021 ± 0.008*	0.59
Peak Knee External Rotation	UT	-0.003 ± 0.002	-0.003 ± 0.002	--
Moment during Landing (BW* BH)	LT	-0.003 ± 0.003	-0.003 ± 0.002	--

Notes. ^: significant differences between upper and lower trunk perturbation locations; *: significant differences between with and without perturbation in each perturbation location.

DISCUSSION: The external perturbation created in this study was around 80 ms after the peak jump height and was consistent among all conditions. The results supported the hypothesis that posterior trunk pulling perturbation would result in variables associated with increased ACL loading during landing. Posterior pulling perturbation demonstrated greater peak vertical GRF, greater peak knee abduction angles, greater peak knee extension and adduction moments, and smaller peak knee flexion angles, regardless of perturbation locations, associated with increased ACL loading during landing. In addition, smaller trunk flexion angles were observed when the posterior perturbation was applied to the upper trunk compared to no perturbation, which was associated with increased ACL injury risk. The findings are consistent with previous

ACL video analyses that contact with the trunk and/or arms near the estimated injury time occupied more than 80% of indirect contact ACL injuries (Song et al., 2023). Such scenarios likely happen in team sports when an opponent grabs another player's trunk backward to halt them during games or an opponent pushes another player in front. The external perturbation applied a direct force to the trunk, leading to a greater posterior velocity of the trunk prior to landing. Such posterior linear velocity likely restricted knee flexion motion (decreased knee range of motion), which may further increase posterior trunk motion and the chance of falling. Consequently, this results in stiffer landing patterns and suboptimal knee controls associated with increased ACL injury risk. In the current study, perturbation also resulted in a greater knee flexion angle at IC, associated with decreased ACL loading. This was likely because of the posterior motion of the trunk relative to the knee. Based on the impulse-momentum theory, the perturbation created in the current study was about half magnitude compared to previous medial-lateral trunk perturbation (Song et al., 2023). Moreover, participants were asked to land with both legs instead of a more challenging single-leg landing task (Song et al., 2023). A riskier scenario of ACL injury might be participants landing harder without flexing their knee prior to landing, consequently leading to stiffer landing patterns when posterior perturbation occurs.

The results generally did not support the hypothesis that the upper trunk perturbation would result in a greater increase in ACL loading variables compared to the lower trunk perturbation. Although a less flexed trunk was observed in the upper trunk perturbation location, no significant difference was found in the knee loading variables. The upper trunk perturbation location was superior to the whole-body COM compared to the lower trunk, which may cause an increased angular momentum in the sagittal plane to rotate the whole body posteriorly. Given a relatively small amount of the perturbation designed in this study (based on the preliminary testing to ensure participants' safety), participants were able to predict the permutation direction and contract their trunk and flex their knees when landing bilaterally to decrease the ACL injury risk. Future studies are warranted to quantify the effects of mid-flight posterior perturbation with greater magnitudes and longer durations.

CONCLUSION: Mid-flight posterior pulling trunk perturbation resulted in greater peak vertical GRF, greater peak knee abduction angles, greater peak knee extension and adduction moments, and smaller peak knee flexion angles associated with increased ACL loading during landing. The increased ACL loading variables are likely due to a greater posterior velocity applied by the perturbation prior to landing. The upper trunk perturbation location resulted in smaller trunk flexion angles but did not significantly increase ACL loading variables compared to the lower trunk perturbation location. These findings contribute to a better understanding of indirect contact ACL injury mechanism and develop effective training strategies under posterior pulling trunk perturbation to prevent ACL injury. For example, teammates/coaches can pull players posteriorly or push players anteriorly during jump-landing training.

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