FALLING RESULTS IN VARIABLES ASSOCIATED WITH DECREASED ACL LOADING DURING LANDINGS AFTER MID-FLIGHT TRUNK PERTURBATION

Yu Song[1], Ling Li[1], Jacob Layer[1], Gerwyn Hughes[2], Derek Smith[1], Margaret Wilson[1], Qin Zhu[1], Boyi Dai[1]

[1]University of Wyoming, Laramie, WY, USA [2]University of San Francisco, San Francisco, CA, USA

Trunk contact is commonly observed near the time of anterior cruciate ligament (ACL) injuries. Soft landings and falling after landing are suggested to decrease ACL injury risk. The purpose was to assess the effect of natural landing, soft landing, and falling techniques on variables associated with ACL loading, including knee flexion, impact forces, knee abduction angles and moments during single-leg landings with or without mid-flight medial-lateral external upper-trunk perturbation. Twenty-eight participants performed single-leg landings using the three landing techniques with or without mid-flight perturbation. Falling resulted in variables associated with decreased ACL loading compared to natural and soft landings, especially for perturbation conditions. Falling techniques are suggested to modify variables associated with ACL loading when the sports environment allows.

KEYWORDS: anterior cruciate ligament, forces, biomechanics, jump-landings, injury risk

INTRODUCTION: Anterior cruciate ligament (ACL) rupture is a severe knee injury in sports (Hughes et al., 2021). A frequent ACL rupture scenario is a single-leg landing with an abnormal landing posture near the time of the ACL injury (Boden et al., 2022). Such abnormal landing posture is commonly characterized by a laterally bent trunk to the injured leg, and the injured knee supporting most of the body weight in an extended and abducted position (Boden et al., 2022; Song et al., 2021). ACL injury video analyses 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., 2021). Meanwhile, mid-flight medial-lateral external trunk perturbation resulted in variables associated with increased ACL loading (greater knee abduction angles and moments, vertical ground reaction force (VGRF), and lateral trunk bending angle) during double-leg jump-landings (Song et al., 2022). In particular, upper trunk perturbation resulted in greater increases in these variables than lower trunk perturbation. The biomechanical connection between medial-lateral trunk perturbation and landing with increased ACL loading variables has been identified. Thus, the next step is to develop effective strategies to modify variables associated with ACL loading under such scenarios. Teaching/training individuals to adopt movement patterns has been used to reduce ACL injury risk. Participants demonstrated decreased VGRF and knee moments and increased knee flexion angles when they attempted to land softly during controlled jump landings (Dai et al., 2015; Li et al., 2020). Furthermore, safe falling techniques after landing have been suggested to be more effective in modifying variables associated with ACL loading compared to the soft landing when the sports environment allows it (Li et al., 2020). However, the effectiveness of soft landings and falling in jump-landing tasks with mid-flight perturbation is unknown.
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 landings with or without mid-flight medial-lateral external upper-trunk perturbation. It was hypothesized that soft landings and falling would result in variables associated with decreased ACL loading compared to natural landings. In addition, falling techniques would be more effective compared to soft landings, particularly in perturbation conditions. Furthermore, the perturbation would result in variables associated with increased ACL loading compared to no-perturbation conditions.

METHODS: The current study was approved by the XXX Institutional Review Board. Based on the smallest effect size of 0.55 in peak VGRF among the three landing techniques and perturbation statuses in previous studies (Li et al., 2020; Song et al., 2022), 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 performed three practice trials for each jump-landing technique. There were three landing techniques, natural landing (landed as they would naturally perform in a sports environment), soft landing (landed as softly as possible with increased knee and hip flexion), and falling (initially landed softly and then smoothly fell laterally to the landing-leg side and rolled toward the hip, back, and shoulders on a gymnastic mat) after landing (Figure 1). Participants started with feet shoulder-width apart and were instructed to jump vertically for maximum height and land on a single leg on the force platform (Bertec, Columbus, OH, USA, 1600 Hz). The mid-flight pushing perturbation was created by a customized apparatus releasing a slam ball as previously described (Song et al., 2022). 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. The landing leg was counterbalanced among participants, while the perturbation status and landing techniques were randomized.
Seventeen retro-reflective markers were placed on the landing leg (Li et al., 2020). Two markers were placed on the diameter of the slam ball. The markers were captured by eight opto-reflective cameras (Vicon, Oxford, UK, 160 Hz). Participants did not know whether a perturbation would be applied prior to the trial, while participants knew the possible perturbation location and direction. Horizontal and vertical ball velocities at ball contact, the timing offset between ball contact and peak jump height, and vertical ball contact location relative to hips were assessed. The lateral trunk bending angle at initial contact (IC) was calculated. Variables associated with ACL loading included knee flexion angle at IC, peak knee flexion and abduction angles during early landing (the first 100 ms after IC), as well as peak VGRF, peak knee extension and adduction moments during early landing. MATLAB 2022a was used for data reduction (MathWorks, Inc., Natick, MA, USA). Repeated-measures analyses of variance (ANOVA) were conducted. Paired t-tests were applied after a significant main effect (p-value ≤ 0.05) was found by ANOVAs.

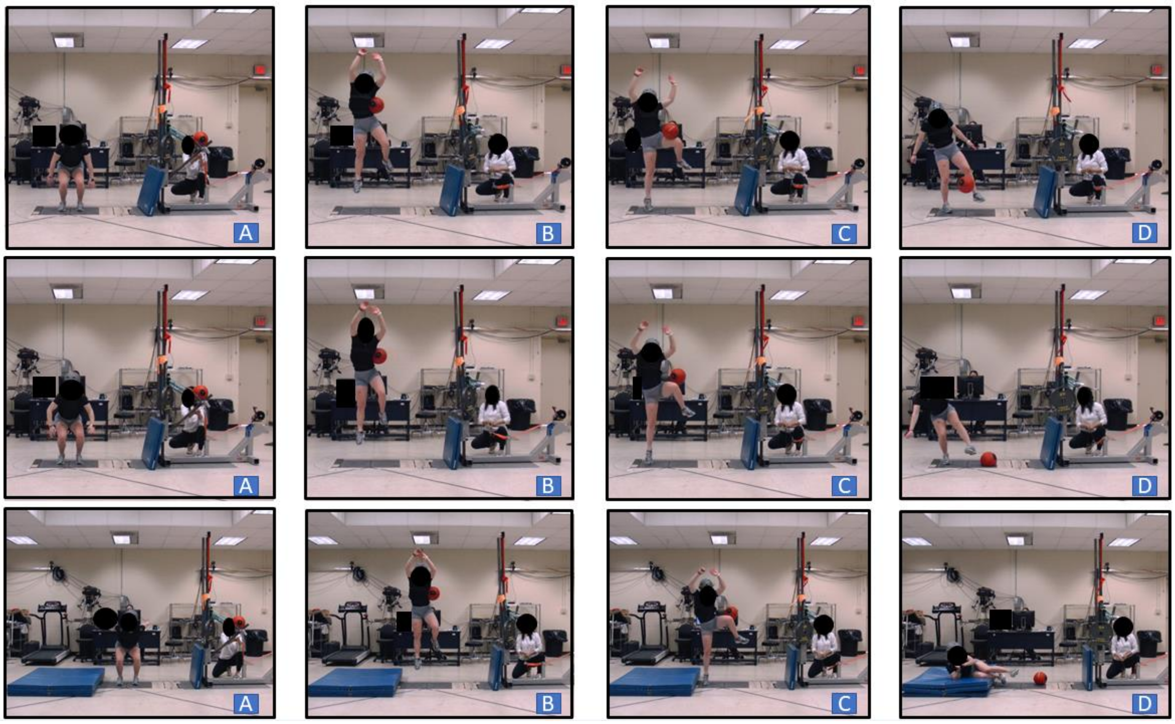

Figure 1: Natural (top row), soft (middle row), and falling (bottom row) landing techniques.

RESULTS: For the perturbation consistency, a greater downward ball velocity was found for the falling condition compared to natural and soft landings (Table 1). The jump height maintained similar regardless of perturbation or landing conditions (Table 2).
Significant interactions between perturbation conditions and landing techniques were found in peak knee flexion angles, peak VGRF, and peak knee adduction moments. The falling

condition demonstrated the greatest lateral trunk bending angles and knee flexion angles and the smallest peak knee abduction angles, peak VGRF, and peak knee extension moments compared to natural and soft landings, regardless of perturbation conditions (Table 2). Decreased peak knee adduction moments were also found for the falling condition compared to the other two conditions when perturbation occurred. In addition, perturbation resulted in increased lateral trunk bending angles, knee flexions angle at IC, peak knee abduction angles, and peak knee adduction moments compared to no perturbation, regardless of landing conditions (Table 2). Increased peak VGRF was also observed with perturbation when participants performed natural and soft-landing conditions but not the falling condition.

Table 1: Means ± standard deviations for ball contact parameters

	Natural Landing	Soft Landing	Falling
Horizontal Ball Velocity (m/s)	5.2 ± 0.2	5.2 ± 0.2	5.3 ± 0.2
Vertical Ball Velocity (m/s)	-0.03 ± 0.22^{B}	-0.05 ± 0.20^{B}	-0.13 ± 0.22^{A}
Timing Offset (ms)	-5.7 ± 33.8	0.6 ± 42.6	-0.1 ± 38.5
Contact Location (m)	0.39 ± 0.07	0.38 ± 0.07	0.39 ± 0.07

Note. ^{A} and ^{B}: ^{A} is significantly greater than ^{B} among landing techniques.

Table 2: Means ± standard deviations of ACL loading variables

		Natural Landing	Soft Landing	Falling
Jump Height (m)	C	0.37 ± 0.09	0.36 ± 0.10	0.37 ± 0.10
	P	0.37 ± 0.10	0.37 ± 0.10	0.36 ± 0.10
Lateral Trunk Bending Angle	C	4.9 ± 2.9^{B*}	4.4 ± 2.8^{B*}	7.3 ± 3.1^{A*}
(°)	P	9.7 ± 3.2^{B*}	9.7 ± 3.2^{B*}	12.6 ± 3.3^{A*}
Knee Flexion Angle at Initial	C	10.2 ± 5.9^{B*}	11.3 ± 6.5^{B*}	12.6 ± 6.5^{A*}
Ground Contact (°)	P	11.4 ± 5.3^{B*}	12.1 ± 6.1^{B*}	14.6 ± 6.6^{A*}
Peak Knee Flexion Angle	C	46.4 ± 8.6^{C}	49.8 ± 8.6^{B}	48.2 ± 7.8^{A*}
during Landing (°)	P	47.4 ± 9.1^{B}	50.6 ± 8.3^{A}	52.0 ± 8.6^{A*}
Peak Knee Abduction Angle	C	-1.6 ± 2.8^{A*}	-1.2 ± 2.9^{B*}	-1.1 ± 2.7^{C*}
during Landing (-) (°)	P	-3.1 ± 2.8^{A*}	-2.8 ± 2.9^{B*}	-2.2 ± 2.8^{C*}
Peak Vertical Ground	C	3.7 ± 0.7^{A*}	3.3 ± 0.7^{B*}	2.9 ± 0.7^{C}
Reaction Force (N/BW)	P	4.0 ± 0.8^{A*}	3.7 ± 0.8^{B*}	2.9 ± 0.7^{C}
Peak Knee Extension Moment	C	-0.13 ± 0.03^{A}	-0.12 ± 0.03^{B}	-0.11 ± 0.03^{C}
(-) during Landing	P	-0.13 ± 0.03^{A}	-0.12 ± 0.03^{B}	-0.11 ± 0.03^{C}
(Nm/(BW*BH))				
Peak Knee Adduction Moment	C	0.010 ± 0.009*	0.008 ± 0.009*	0.007 ± 0.011*
during Landing (Nm/(BW*BH))	P	0.024 ± 0.013^{A*}	0.023 ± 0.014^{A*}	0.014 ± 0.013^{B*}

Note. C: no-perturbation; P: perturbation; BW: body weight; BH: body height; ^{A}, ^{B}, and ^{C}: based on paired t-tests results, ^{A} is the greatest, ^{B} is the second greatest, ^{C} is the least among landing techniques; *: significantly different between no-perturbation and perturbation for each landing technique.

DISCUSSION: The external perturbation created by the slam ball was generally consistent among landing techniques. A slightly greater downward ball velocity (0.1 m/s) was observed for the falling technique compared to natural and soft landings, which was likely due to a greater lateral trunk bending angle.

The findings supported the hypothesis that soft landings would result in variables associated with decreased ACL loading compared to natural landings. Researchers reported that soft landings resulted in increased knee flexion angle, decreased peak VGRF, and decreased peak knee extension moment compared to the natural landing for both single-leg and double-leg landings (Li et al., 2020). However, less protective effects of soft landings were shown in single-leg landings compared to double-leg landings. It is suggested that the effectiveness of soft landings might be limited when the task is more challenging. The current findings agreed with previous studies that soft landings could result in variables associated with decreased ACL loading regardless of perturbation statuses. However, the effectiveness of a soft-landing technique was less for perturbation conditions than for no-perturbation conditions. The soft landing also did not appear to be effective in decreasing frontal plane knee moments.

The results supported the hypothesis that the falling technique would be more effective in decreasing ACL loading variables compared to the soft and natural landings. First, the falling technique allowed a lower whole-body center of mass (COM) position during landing through increased knee and hip flexion (Li et al., 2020). The significantly greater peak knee flexion angle of the falling technique supported that the participants showed a greater range of motion in the vertical direction to dissipate the landing forces. Thus, the lowest peak VGRF and knee extension moment were found for the falling technique, which agreed with previous findings (Li et al., 2020). Second, 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 needed to be absorbed by the lower limbs in a short amount of time. In contrast, the falling technique allowed the whole-body COM to move out of the base of support and involve other body parts, such as the hips and trunk, to decelerate the downward and lateral velocities over a longer time. Due to the removal of the constraint of the base of support, participants actively bent their trunks to the falling direction. While lateral trunk bending to the landing leg has been identified as a risky movement pattern for ACL injuries, this finding suggests that it might not be as risky if participants were not constrained by the landing foot and allowed themselves to fall to the ground. In summary, when the sports environment allows, falling appears to be an effective strategy to modify variables associated with ACL loading compared to soft landings, especially in perturbation conditions.

Lastly, the results generally supported the hypothesis that the mid-flight external trunk perturbation would result in increased peak VGRF and knee abduction angles and moments compared to no perturbation conditions. An upper-trunk contact applied a direct force acting at a distance from the whole-body COM to cause increased horizontal velocity and whole-body angular momentum. The findings were consistent with a previous study that documented increased ACL loading variables for the contralateral leg as a result of mid-flight pushing perturbation during a double-leg landing (Song et al., 2022). However, perturbation increased knee flexion angle at IC and peak value, which are associated with decreased ACL loading. This may be a compensatory strategy to mitigate the increased impact forces and frontal plane knee moments. A riskier scenario in sports would be that participants experienced greater landing forces and frontal plane moments due to mid-flight perturbation but did not engage in increased knee flexion prior to landing, possibly due to greater perturbation, limited muscle strength, or concurrent cognitive tasks.

CONCLUSION: Soft landings resulted in variables associated with decreased ACL loading compared to natural landings but were less effective for perturbation conditions. Falling further demonstrated variables associated with decreased ACL loading variables compared to natural and soft landings, particularly for perturbation conditions. The falling technique is recommended to be incorporated into jump-landing training programs to modify variables associated with ACL loading when the sports environment allows, with the goal of decreasing indirect contact ACL injuries.

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