FALLING AS A STRATEGY TO DECREASE KNEE LOADING DURING LANDINGS

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Anterior cruciate ligament injuries often occur when individuals land with a single leg. Falling has been suggested as a potential strategy to decrease knee loading during landings. The purpose was to compare knee flexion angles, peak impact forces, and peak knee extension moments among natural landings, soft landings, and falling in forward and vertical landing tasks under single or double leg conditions. Sixteen male and sixteen female participants completed each landing condition, while three-dimensional kinematics and ground reaction forces (GRF) were collected. In the natural landing condition, participants landed as they would in a sport setting. In the soft-landing condition, participants landed as softly as possible with increased knee and hip flexion. In the falling condition, participants initially landed softly and then fell forward or backward onto a mat in the forward and vertical landing tasks, respectively. Knee flexion angles at initial contact and peak knee flexion angles were generally the greatest for the falling, the second greatest for the soft landing, and the least for the natural landing. Peak vertical and posterior GRF and knee extension moments during early landing were generally the least for the falling, the second least for the soft landing, and the greatest for the natural landing. When the sports environment allows, falling appears to be an innovative strategy to decrease knee loading when individuals must land with a single leg and sub-optimal body postures.

KEYWORDS: ACL, Injury Prevention, Forces, Impact, Kinetics.

INTRODUCTION: During landing activities, individuals progressively decelerate the downward and horizontal velocities resulting from a jump or a drop height through the interactions between the body and the surface. Excessive loading associated with abnormal landing patterns may cause lower extremity injuries. For example, anterior cruciate ligament (ACL) injuries are often observed when individuals land with a single leg with small knee flexion (Dai et al., 2014). Small knee flexion angles and increased tibial anterior shear forces are strongly associated with ACL loading (Dai et al., 2014). Developing effective landing strategies that target ACL loading mechanisms has implications for ACL injury prevention.
One technique to modify lower extremity loading during landing is to land softly. Instructions and feedback can immediately result in soft landing patterns, characterized by increased knee and hip flexion and decreased impact forces (Dai et al., 2015; Zhang et al., 2000). The effectiveness of soft landing, however, has primarily been examined in double-leg landings (Dai et al., 2015; Zhang et al., 2000). While single-leg landings result in greater loading compared to double-leg landings (Donohue et al., 2015), limited studies have examined the instruction of a soft landing style on biomechanics in single-leg landings (Laughlin et al., 2011). Previous studies have instructed participants to complete landing tasks in a standing posture with one or two feet contacting the ground (Dai et al., 2015; Laughlin et al., 2011; Zhang et al., 2000). This requirement of keeping the centre of mass above the feet could underline the role of lower extremity strength in posture control, as greater strength is likely needed to achieve greater lower extremity joint angles without falling, especially in single-leg landings. On the other hand, it is unknown whether falling after landing would provide advantages for individuals to achieve less knee loading. A kinematic analysis of Parkour landings revealed that a forward roll in landing allowed athletes to decrease initial vertical and horizontal velocities over a longer duration, which was likely to decrease peak lower extremity loading (Dai et al., In Press). Two recent studies have suggested falling as a landing strategy after excessive mid-flight trunk motion as the constraint of keeping the centre of mass over the feet might predispose

individuals to experience increased knee loading (Davis et al., 2019; Hinshaw et al., 2018). For example, when volleyball and badminton players extend their trunks in flight to spike a ball or smash a shuttlecock, they are likely to move their centre of mass away from their knees and increase their knee loading during landings (Davis et al., 2019). Evaluating the effect of falling on ACL loading variables could provide information for considering falling as a potential ACL injury prevention strategy.
The purpose was to compare knee flexion angles, impact forces, and knee extension moments among natural landings, soft landings, and falling in forward and vertical landings under single or double leg conditions. We hypothesized that 1) soft landings would result in increased knee flexion angles and decreased impact forces and peak knee extension moments compared to natural landings; 2) falling would result in increased knee flexion angles and decreased impact forces and peak knee extension moments compared to soft and natural landings.

METHODS: Sixteen males and sixteen females participated (age: 22.0 ± 2.9 years; height: 1.75 ± 0.06 m; mass: 69.9 ± 10.5 kg). Inclusion and exclusion criteria were previously described (Davis et al., 2019). This study was approved by the University of Wyoming Institutional Review Board. Retro-reflective markers were placed on the 7th cervical vertebra and bilateral acromioclavicular joints and greater trochanters. On the testing leg (preferred jumping leg to for distances), markers were placed on the 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. Kinematic data were recorded using eight cameras at 160 Hz (Vicon, Oxford, UK). Ground reaction forces (GRF) were collected using one force platform at 1600 Hz (Bertec, Columbus, OH, USA).
Participants performed a minimum of three practice trials and three recorded trials of a forward or vertical landing task with the testing leg or both legs. The forward landing task required participants to jump forward from a 30 cm box placed half of the participant's body height from the force platform and land with either the testing leg or both legs (Figure 1). For the natural landing, participants landed as they would in a sport setting. For the soft landing, participants landed as softly as possible with increased knee and hip flexion throughout the landing (Dai et al., 2015). For the falling, participants initially landed softly and then smoothly fell forward and rolled toward their hands and shoulders (Dai et al., In Press). The vertical landing task required participants to jump vertically and reach to touch a basketball aligned above their heels at 75% of the participant's maximum vertical jump height, and then land back with either the testing leg or both legs (Figure 2). The instructions for natural and soft landings were the same. For the falling, participants initially landed softly and smoothly fell backward on their hips with hands by their sides (Davis et al., 2019). A gymnastics mat was used in the falling conditions.

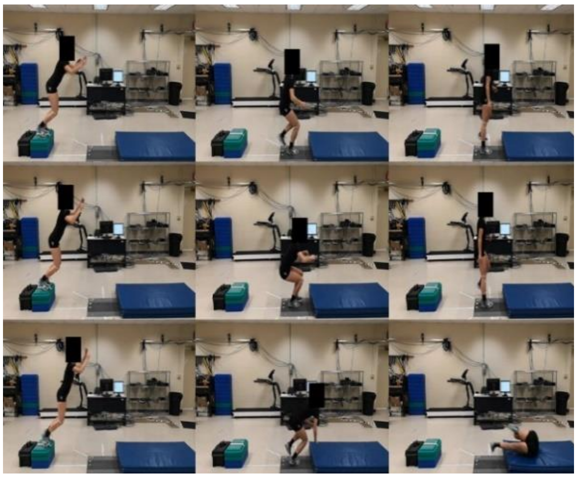

Figure 1. The single-leg forward landing with the natural landing (top), soft landing (middle), and falling techniques (bottom)

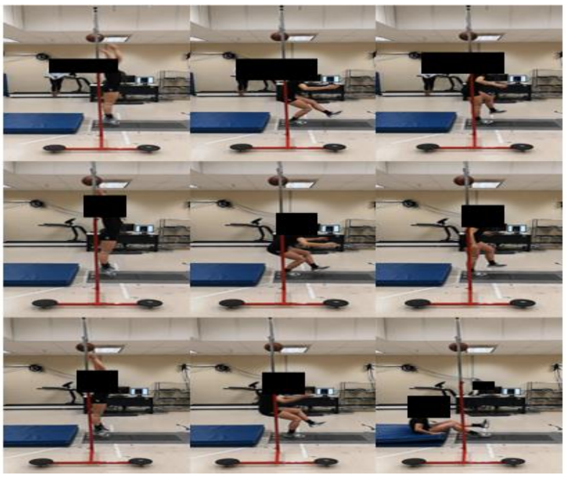

Figure 2. The single-leg vertical landing with the natural landing (top), soft landing (middle), and falling techniques (bottom)

Knee flexion angles at initial contact, peak knee flexion angles, peak vertical GRF, peak posterior GRF, and peak knee extension moments during the first 100 ms after initial contact were extracted (Davis et al., 2019). For each landing task (forward or vertical landing, single or double legs), dependent variables were compared among the three techniques (natural landing, soft landing, and falling) using the repeated measures analyses of variance (ANOVA), followed by paired t-tests. A type-I error rate of 0.05 was used for statistical significance.

RESULTS: One male participant did not complete the vertical landing task. Descriptive data and statistical significance are presented in Table 1. The effect of landing techniques for each landing task is grouped, where A > B > C at a Type-I rate less than 0.05. Knee flexion angles at initial contact and peak knee flexion angles were generally the greatest for the falling, the second greatest for the soft landing, and the least for the natural landing. Peak vertical GRF, posterior GRF, and knee extension moments during early landing were generally the least for the falling, the second least for the soft landing, and the greatest for the natural landing.

Table 1. Means ± standard deviations of dependent variables for different landing conditions

		Forward Landing (n=32)			Vertical Landing (n=31)		
		Natural Landing	Soft Landing	Falling	Natural Landing	Soft Landing	Falling
Knee Flexion Angles at Initial Contact (°)	Double Legs	18.5 ± 5.9 C	22.2 ± 6.8 B	26.1 ± 8.8 A	16.3 ± 6.0 C	18.1 ± 7.2 B	23.6 ± 7.8 A
	Single leg	11.1 ± 4.9 C	12.1 ± 5.1 B	14.4 ± 6.7 A	11.1 ± 5.6 B	11.7 ± 5.8 B	14.6 ± 6.6 A
Peak Knee Flexion Angles during Early Landing (°)	Double Legs	73.6 ± 7.8 C	79.2 ± 8.6 B	82.3 ± 8.8 A	60.7 ± 12.2 C	64.6 ± 11.5 B	72.3 ± 9.9 A
	Single leg	54.1 ± 7.4 C	56.2 ± 7.5 B	60.1 ± 7.5 A	50.1 ± 9.8 C	51.5 ± 10.6 B	59.6 ± 10.1 A
Peak Vertical Ground Reaction Forces during Early Landing (Body Weight)	Double Legs	2.9 ± 0.7 A	2.4 ± 0.6 B	1.7 ± 0.6 C	2.3 ± 0.9 A	1.9 ± 0.6 B	1.6 ± 0.5 C
	Single leg	4.4 ± 0.6 A	4.0 ± 0.6 B	2.9 ± 0.7 C	3.9 ± 0.9 A	3.6 ± 0.9 B	3.0 ± 0.7 C
Peak Posterior Ground Reaction Forces (-) during Early Landing (Body Weight)	Double Legs	-0.8 ± 0.2 A	-0.7 ± 0.2 B	-0.5 ± 0.1 C	-0.5 ± 0.1 A	-0.4 ± 0.1 B	-0.4 ± 0.1 AB
	Single leg	-1.2 ± 0.2 A	-1.1 ± 0.3 B	-0.7 ± 0.2 C	-0.6 ± 0.2 B	-0.6 ± 0.2 B	-0.7 ± 0.1 A
Peak Knee Extension Moments (-) during Early Landing (Body Weight * Body Height)	Double Legs	-0.11 ± 0.02 A	-0.10 ± 0.02 B	-0.08 ± 0.02 C	-0.11 ± 0.03 A	-0.10 ± 0.02 B	-0.08 ± 0.02 C
	Single leg	-0.16 ± 0.03 A	-0.16 ± 0.03 A	-0.14 ± 0.03 B	-0.17 ± 0.04 A	-0.16 ± 0.04 B	-0.13 ± 0.03 C

Note: The effect of landing techniques for each landing task is grouped, where A > B > C at a Type-I rate less than 0.05.

DISCUSSION: The findings support the hypothesis that the soft landing would result in increased knee flexion angles and decrease impact forces and peak knee extension moments compared to the natural landing. Consistent with a previous study (Dai et al., 2015), the current findings showed that simple verbal instruction of soft landings resulted in landing mechanics associated with decreased ACL loading. Compared to the single-leg soft landing, the double-leg soft landing allowed greater knee flexion angles and a larger reduction in impact forces and knee extension moments. The decreased changes associated with single-leg landings could be related to lower extremity strength, which limited the peak joint angles participants could achieve in a standing posture. The modulating effect of soft landings on ACL loading variables in single-leg landings could be further diminished as landing velocities increase due to the additional demands on lower extremity strength. While ACL injuries typically occur during single-leg landings (Dai et al., 2014), the reduction of ACL loading associated with soft landing techniques could be limited for single-leg landings compared to double-leg landings.

The findings also support the hypothesis that falling would result in increased knee flexion angles and decrease impact forces and peak knee extension moments compared to both soft and natural landings. Greater posterior GRF are direct indicators of knee extension moments and are associated with increased tibial anterior shear forces (Yu et al., 2006). For the current forward landing task, as participants came to a complete stop at the end of both natural and soft landings, the forward velocity was largely decelerated simultaneously with the downward velocity, resulting in greater posterior GRF. On the other hand, as participants were rolling forward in the falling condition, a large amount of the forward velocity was likely maintained and resulted in decreased posterior GRF during early landing. In addition, falling allowed participants to have a greater range of motion in the vertical direction because their centre of mass was no longer constrained by the feet. This resulted in greater force dissipation in the vertical direction as well as the involvement of the upper extremities and trunk to decelerate the whole body. The decreased impact GRF in both vertical and posterior directions were consistent with overall decreases in knee extension moments. An extended trunk at initial contact of landing has been previously shown to create external knee flexion moments, which need to be counterbalanced by internal knee extension moments to maintain a standing posture (Davis et al., 2019). The current vertical landing task simulated this performance demand by placing the target slightly behind the participant's head. Compared to the natural and soft landings, in which participants had to maintain a standing posture, participants did not have to resist the external knee flexion moments in the falling. Instead, falling allowed them to move their centre of mass behind their feet, while vertical velocities were absorbed through a greater range of motion as well as through the contact between the hips and the surface. Meanwhile, it is reasonable to observe that the decreases in knee extension moments were mainly associated with decreased vertical GRF but not posterior GRF for the vertical landing task, as it mainly involved motion in the vertical but not the anterior direction.

CONCLUSION: Single-leg landings were associated with increased knee loading compared to double-leg landings, particularly when individuals had to constrain their centre of mass within their feet. The effectiveness of soft landings in reducing knee loading, however, was limited for single-leg landings compared to double-leg landings. Falling demonstrated landing biomechanics associated with the least knee loading compared to both natural and soft landings. When the sports environment allows, falling appears to be an innovative strategy to decrease knee loading when individuals must land with a single leg and sub-optimal body postures. Progressive training of controlled and safe falling techniques with an aim to protect the ACL while minimizing other injury risk is warranted in future studies.

REFERENCES

Dai, B., Garrett, W.E., Gross, M.T., Padua, D.A., Queen, R.M., & Yu, B., (2015). The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. *The American Journal of Sports Medicine,* 43, 466-474.
Dai, B., Layer, J.S., Hinshaw, T.J., Cook, R.F., & Dufek, J.S., (In Press). Kinematic analyses of parkour landings from as high as 2.7 meters. *Journal of Human Kinetics*.
Dai, B., Mao, D., Garrett, W.E., & Yu, B., (2014). Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs. J*ournal of Sport and Health Science,* 3, 299-306.
Davis, D.J., Hinshaw, T.J., Critchley, M.L., & Dai, B., (2019). Mid-flight trunk flexion and extension altered segment and lower extremity joint movements and subsequent landing mechanics. *Journal of Science and Medicine in Sport,* 22, 955-961.
Donohue, M.R., Ellis, S.M., Heinbaugh, E.M., Stephenson, M.L., Zhu, Q., & Dai, B., (2015). Differences and correlations in knee and hip mechanics during single-leg landing, single-leg squat, double-leg landing, and double-leg squat tasks. *Research in Sports Medicine,* 23, 394-411.
Hinshaw, T.J., Davis, D.J., Layer, J.S., Wilson, M.A., Zhu, Q., & Dai, B., (2019). Mid-flight lateral trunk bending increased ipsilateral leg loading during landing: a center of mass analysis. *Journal of Sports Sciences*, 37, 414-423.
Laughlin, W.A., Weinhandl, J.T., Kernozek, T.W., Cobb, S.C., Keenan, K.G., & O'Connor, K.M., (2011). The effects of single-leg landing technique on ACL loading. *Journal of Biomechanics*, 44, 1845-1851.
Yu, B., Chappell, J.J., & Garrett, W.E., (2006). Responses to letters to the editor. *The American Journal of Sports Medicine,* 34, 312-315.
Zhang, S.N., Bates, B.T., & Dufek, J.S., (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise,* 32, 812-819.

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