Abstract

Objectives: To assess the effect of mid-flight trunk flexion and extension on the movements of body segments and lower extremity joints and subsequent landing mechanics during a jump-landing task.

Design: Participants performed three jump-landing conditions in a randomized order.

Method: Forty-one participants completed jump-landing trials when performing three different mid-flight trunk motion: reaching forward, reaching up, and reaching backward. Whole-body kinematic and ground reaction force data were collected.

Results: The reaching backward condition resulted in a more posteriorly positioned upper body center of mass (COM) and more anteriorly positioned pelvis COM, legs COM, hip, and knee joint positions relative to the whole-body COM in flight and at initial contact of landing. The reaching backward condition showed the least hip flexion and ankle plantarflexion angles at initial contact as well as the least hip and knee flexion angles and the greatest ankle dorsiflexion angles at 100 ms after landing. The reaching backward condition also demonstrated the greatest peak posterior ground reaction force, peak and average knee extension moments, peak and average hip flexion moments, and peak knee varus moments within the first 100 ms after landing. Opposite changes were observed for the reaching forward condition.

Conclusions: Mid-flight trunk extension resulted in body postures that predisposed individuals to land with increased knee extension and varus moments and decreased knee flexion angles, which are indirectly associated with increased ACL loading. These findings may help to understand altered trunk motion during certain ACL injury events and provide information for developing jump-landing training strategies.

Keywords: ACL; Knee; Injury; Biomechanics; Kinematics; Kinetics

1. Introduction

The knee joint endures injury at an elevated rate, and rupturing the anterior cruciate ligament (ACL) specifically is both common and potentially devastating.[1-3] Non-contact movements such as jump-landing and cutting are the most common ACL injury circumstances.[4] Literature has demonstrated that "stiff" landings, often characterized by decreased knee and hip flexion and increased ground reaction forces (GRF) and knee moments, are associated with increased ACL loading[5-8] and ACL injury risk.[9,10] Like many sport maneuvers, landing patterns are likely responses to the sports environment; therefore, understanding factors that can result in stiff landings may help athletes better prepare for such situations with elevated injury risk.

Trunk position has been demonstrated as a necessary consideration in examining landing mechanics linked to ACL injuries. In the frontal and transverse planes, increased lateral trunk bending and rotation has been observed when ACL injuries occur.[11-13] Regarding the sagittal plane, Boden et al.[14] reported that increased hip flexion was observed when basketball players sustained ACL injuries. Sheehan et al.[15] showed an increased distance between the whole-body center of mass (COM) and base of support at landing was the primary contributor to ACL injuries, rather than increased hip flexion. Indeed, hip flexion resulting from trunk flexion may place the whole-body COM closer to the knee and decrease knee loading. Blackburn and Padua[6] found that active trunk flexion increased hip and knee flexion and decreased impact GRF and quadriceps activation during a double-leg landing. Similarly, Shimokochi and Shultz[7] showed that landing with increased trunk flexion decreased impact GRF and knee moments during a single-leg landing. These studies suggested that trunk flexion was likely to decrease ACL loading, although the relationship between the whole-body COM and the lower extremity joints was not quantified. In addition, the protocols mentioned above instructed participants to intentionally flex their trunk to influence landing mechanics. How performance demands themselves may predispose individuals to land with different trunk alignments is not clear.

Mid-flight trunk motion is integral to many sports and may affect subsequent landing mechanics. Newton's 1st Law defined the parabola-shaped trajectories of the whole-body COM in flight. As the trunk comprises nearly half of the whole-body mass, its movement in one direction in flight is likely opposed by movement of the rest of the body. Hinshaw et al.[16] instructed participants to bend their trunk mediolaterally after a maximal countermovement jump. When the trunk COM was moved in the bending direction, other body segments countered this movement in the opposite direction. Consequently, more weight was placed on the knee ipsilateral to the trunk bending direction during landing. Quantifying mid-flight COM in the anterior-posterior direction will provide additional information for understanding the role of trunk motion on ACL injury risk.

Therefore, the purpose was to assess the effect of mid-flight trunk flexion and extension on the movements of body segments and lower extremity joints and subsequent landing mechanics during a jump-landing task. It was hypothesized that both men and women would move their trunk COM backward and their pelvis and legs COM forward when they reached backward mid-flight. In addition, the hip and knee joints would be positioned more anteriorly to the whole-body COM mid-flight and at initial contact of landing for the reaching backward condition. The landing posture imposed by the reaching backward condition was hypothesized to decrease hip and knee flexion angles and increase impact GRF, knee extension and varus moments, hip flexion moments, and knee valgus angles during landing for both men and women. In contrast, opposite changes were hypothesized for the reaching forward condition.

2. Methods

Based on previous studies,[6,7] a medium to large effect size was expected among the jump-landing conditions. A sample size of 34 was required to achieve a medium effect size of 0.5 for a paired t-test to achieve a power of 0.8 at a type-I error rate of 0.05. Participants included twenty-three females (age: 22.1 ± 3.6 years; height: 1.67 ± 0.07 m; mass: 63.7 ± 11.1kg; exercise and sport participation: 8.59 ± 4.47 hours/week) and eighteen males (age: 20.6 ± 5.5 years; height: 1.82 ± 0.08 m; mass: 80.4 ± 11.3kg; exercise and sport participation: 8.55 ± 3.78 hours/week). Thirty-four participants had experience in basketball, volleyball, soccer, or American football. Seven participants had experience in tennis, track and field, rugby, or dance. Detailed inclusion and exclusion criteria were previously described (Appendix).[17] The current study was approved by the XXX Institutional Review Board. Participants signed a consent form prior to participation.

Participants wore a baseball cap, spandex clothes, and standard shoes and performed a generalized warm-up.[18] Forty-four retro-reflective markers were placed on the participant to establish a whole-body model.[16] After a static standing trial, participants completed jump-landing trials in each of three different conditions (Figure 1). Each condition began with participant's feet placed shoulder-width apart on two force platforms. Upon instruction, participants jumped for maximal height and landed with each foot on a force platform. As they reached maximal jump height, participants reached their hands and bent their trunk as far as they felt comfortable in the direction corresponding to the condition: Backward, Up, or Forward. Trials were redone if participants failed to land back on force platforms. However, participants were allowed to take steps to regain balance after landing. No other instructions were given on landing techniques. Each condition included three official trials, prefaced by at least two practice jumps. The order of the three jump-landing conditions was randomized. Participants had a minimum of 30-seconds rest between two trials to minimize fatigue. Kinematic data were captured using eight cameras at 160 Hz (Bonita 10, Vicon Motion System Ltd, Oxford, UK). GRF were recorded using two force platforms at 1600 Hz (Bertec FP4060-10, Bertec Corporation, Columbus, OH, USA).

Kinematic and GRF data were filtered using fourth-order Butterworth low-pass filters at 15 Hz and 100 Hz, respectively. The use of 15 Hz for kinematic data was consistent with previous studies.[19] 100 Hz was selected as high-frequency noise was observed for GRF data. A total of fifteen segments were defined to calculate the whole-body COM position.[16] In addition, a trunk component was defined as all the segments above the pelvis. A leg component was defined as all segments below the pelvis. The COM positions of the trunk, pelvis, and leg components as well as the positions of middle points of bilateral hips, knee, and ankles relative to the whole-body COM in the anterior (+) - posterior (-) direction were calculated from takeoff to initial contact of landing. In addition, lower extremity joint angles were calculated as Cardan angles between adjacent segment reference frames. An inverse dynamic approach was used to calculate internal lower extremity joint resultant moments.[19] Joint angles during static trials were subtracted from those during jump-landing trials. Joint resultant moments were expressed in proximal segment reference frames and normalized by individual participant's body weight and height. GRF were normalized by individual participant's body weight.

To assess landing kinematics and kinetics associated with ACL loading,[19] hip flexion, knee flexion, and ankle dorsiflexion angles at both initial contact and 100 ms after landing were identified. In addition, peak bilateral vertical GRF, peak bilateral posterior GRF, peak and average knee extension moments, peak and average hip flexion moments, peak knee varus moments, and peak knee valgus angle were extracted within the first 100 ms after landing as most ACL injuries occur during this period.[20,21] Jump height was calculated to assess jump performance. Calculations were performed using customized subroutines developed in MATLAB (MathWorks Inc. Natick, MA, USA).

Ensemble curves with the 95% confidence interval of the mean were calculated for mid-flight segment COM and lower extremity joint positions for the three jump-landing conditions for all participants. Right and left hip, knee, and ankle joint angles and moments changed similarly among the three jump-landing conditions, so the two sides were averaged for analyses. Dependent variables were compared among the three jump-landing conditions and between men and women using repeated measures analyses of variance (ANOVA). Sex was included as an independent variable as women have shown higher ACL injury rates than men in several sports events.[2] A significant ANOVA test was followed by t-tests. The study-wide false discovery rate for all paired t-tests was controlled at 0.05.[22] The effect sizes of pairwise comparisons were assessed using Cohen's dz, with Cohen's dz ≥ 0.8 considered "large," $0.5 \leq$ Cohen's dz < 0.8 considered "medium," and Cohen's dz < 0.5 considered "small."[23] Statistical tests were performed using SPSS Statistics 24 software (IBM Corporation, Armonk, NY, USA).

3. Results

As shown in Figure 2, compared to the Up condition, participants moved the upper body COM in the posterior direction and the pelvis COM, legs COM, and the hip joint in the anterior direction from takeoff to initial landing for the Backward condition. Opposite changes were observed for the Forward condition. Knee positions were similar among the three conditions during the first 80% of the flight phase. The knee moved anteriorly prior to initial contact of landing, with the greatest movements for the Backward condition. The ankle moved in the same direction as the upper body COM during most of the flight but became similar across the three conditions at initial contact of landing.

Significant ANOVAs were found for most discrete variables (Table 1). The largest p value for a significant t-test was 0.03 after the adjustment for the false discovery rate. Men jumped higher than women for all three jump-landing conditions. For both men and women, jump height was the greatest for the Up condition with large effect sizes. The Backward condition resulted in a more posteriorly positioned upper body COM and more anteriorly positioned pelvis COM, legs COM, and hip and knee joint positions relative to the whole-body COM at initial contact of landing for both men and women. Opposite changes were observed for the Forward condition. The effect sizes of these changes were large.

Regarding landing kinematics, the Backward condition showed the least hip flexion and ankle plantarflexion angles at initial contact as well as the least hip and knee flexion angles and the greatest ankle dorsiflexion angles at 100 ms after landing for both men and women, while opposite changes were observed for the Forward condition. The effect sizes of these changes were mostly medium to large. The Forward condition also resulted in the greatest knee flexion angles at initial contact with large effect sizes. For landing kinetics, men demonstrated greater peak vertical GRF, peak posterior GRF, peak and average knee extension moments, peak hip flexion moments, and peak knee varus moments than women for all three jump-landing conditions. For both men and women, the Backward condition demonstrated the greatest peak posterior GRF, average and peak knee extension moments, average and peak hip flexion moments, and peak knee varus moments, while opposite changes were observed for the Forward condition. The effect sizes of these changes were large.

4. Discussion

The purpose was to quantify the effects of mid-flight trunk flexion and extension on body segment and lower extremity joint movements and subsequent landing mechanics. The findings support the hypothesis that mid-flight trunk flexion and extension would cause different movement patterns for body segments and lower extremity joints for both men and women. For the Backward condition, participants extended the trunk and posteriorly moved the upper body COM relative to the whole-body COM. Consequently, the pelvis and legs moved in the opposite direction. Opposite directional changes were observed in the Forward condition.

Regarding lower extremity joint movements, the movements of the hip joint were similar to the pelvis, as they were closely located. The ankle joint moved in the opposite direction compared to the hip joint, which could be explained by the conservation of angular momentum around the whole-body COM in flight. For the Backward condition, as the upper body rotated counterclockwise, the legs rotated clockwise to keep a constant angular momentum. Since the hip and ankle joints moved in opposite directions, the knee joint positions were relatively similar among the three conditions in the first 80% of flight. However, the ankle joint positions became closer to the whole-body COM prior to initial contact for all three conditions. This could be interpreted as participants controlling the base of support to better align with the whole-body COM in attempts to prevent falling during landing. For the Backward condition, participants utilized this “ankle focused” strategy, while the changes in upper body and pelvis COM were relatively small at the end of flight. Greater anterior movements of the ankle along with less posterior movements of the hip resulted in an anteriorly positioned knee.

The findings generally support the hypothesis that the Backward condition would decrease hip and knee flexion angles and increase posterior GRF, knee extension and varus moments, and hip flexion moments during landing for both men and women. Increased ankle dorsiflexion was also observed for this condition. Men demonstrated increased kinetic variables than women, which could be related to their greater jump height and therefore increased kinetic energy to absorb during landing. The changes in landing biomechanics as a function of trunk flexion were generally consistent with previous studies.[6,7] For the Backward condition, the knee and hip were positioned more anterior to the whole-body COM, resulting in greater external knee flexion and hip extension moments. Consequently, greater internal knee extension and hip flexion moments were generated to maintain postural stability. The changes in peak posterior GRF were reflections of changes in hip and knee moments, as contraction of both knee extensors and hip flexors would produce posterior GRF during landing.

Regarding kinematics, the anterior location of the knee joint lead participants to generate greater knee extension moments for the Backward condition. Participants likely limited knee flexion angles to avoid further increases in knee extension moments. In addition, more flexion of the knee joint may induce even greater posterior movement. Participants could move the whole-body COM anteriorly by increasing hip flexion and ankle dorsiflexion angles, subsequently allowing for greater knee flexion without increasing posterior movement. However, flexion of the hip requires participants to overcome significant external hip extension moments. Overall, the landing posture at initial contact for the Backward condition placed participants at mechanical disadvantages for further knee and hip flexion, although participants increased ankle dorsiflexion to compensate. In contrast, for the Forward condition, the whole-body COM was more anteriorly positioned relative to the knee. The external hip flexion moments facilitated hip flexion thereby moving the whole-body COM anteriorly to allow for knee flexion.

The current findings may provide additional information to understand certain ACL injuries associated with altered trunk motion. The quadriceps force, the primary contributor to knee extension moments, can load the ACL through an anterior tibial shear force, and its effect on ACL load was greater at small knee flexion angles.[24] In vivo studies have also demonstrated a negative relationship between knee flexion angles and ACL length during walking and jump-landing.[25,26] Sheehan et al.[15] observed increased distances between the whole-body COM and base of support in the sagittal plane, greater thigh segment angles, and less trunk segment angles at landing in ACL injury events, and suggested that increased quadriceps contraction was likely a contributor to these injuries. The current findings are generally consistent with these observations, but also highlight the importance of quantifying the relative positions between the whole-body COM and lower extremity joints. While participants attempted to align their whole-body COM and base of support during landing, this resulted in anteriorly positioned knee and hip joints, subsequently affecting joint moments and kinematics. In addition, the mid-flight trunk motion was imposed by reaching tasks that were commonly performed in sport. Successfully completing these goals can be integral to many sports, emphasizing the importance of incorporating performance demands into jump-landing tasks.

The findings may provide information for training aimed at modifying jump-landing mechanics associated with ACL loading. First, landing with trunk flexion resulted in biomechanics associated with decreased ACL loading and should be considered when the sport environment allows. Second, after completing tasks that require mid-flight trunk extension, individuals may try to use the remaining flight phase to actively flex the trunk prior to landing.

Core proprioception and strength may be important for this strategy.[27] In addition, increasing pre-landing knee and hip flexion can increase flight time for adjusting trunk position and help prepare for a soft landing. Last, when the trunk extension is excessive and cannot be adjusted prior to landing, individuals may consider a safe fall to the back. Long-term training is likely needed to successfully complete these jump-landing techniques.

The current study had several limitations. First, although effort was spent to simulate sports-specific tasks, the protocol occurred in a controlled setting without including additional in-game factors such as opponents, action-reaction, and shift of attention.[17,28] Second, participants were instructed to jump for maximal height and reach for maximal distance; however, participants still landed with a close alignment between whole-body COM and base of support alignment and the extent of trunk flexion and extension was not controlled. Third, participants were limited to recreational athletes with a variety of sports experience. Other populations (e.g. elite athletes) may demonstrate different landing mechanics. Last, joint angles and moments, which were indirectly associated with ACL loading, were calculated, while no in-vivo data regarding ACL loading were measured.

5. Conclusion

Mid-flight trunk extension resulted in more anteriorly positioned hip and knee joints relative to the whole-body COM. This predisposed individuals to land with greater internal knee extension, varus, and hip flexion moments and decreased knee and hip flexion angles during early landing, which are indirectly associated increased ACL loading. In contrast, mid-flight trunk flexion facilitated landing with decreased knee extension and varus moments and increased knee flexion. These findings may help explain altered trunk motion observed during certain ACL injury events and provide information for developing jump-landing training strategies.

Practical implications

- Landing with increased trunk flexion should be considered when the sport environment allows.
- Mid-flight trunk extension may result in landing mechanics associated with increased ACL loading.
- Individuals should be aware of the altered landing mechanics resulting from mid-flight trunk motion and implement effective landing strategies for these situations.

References

1. Kay MC, Register-Mihalik JK, Gray AD, et al. The epidemiology of severe injuries sustained by National Collegiate Athletic Association student-athletes, 2009-2010 through 2014-2015. *J Athl Train* 2017; 52(2):117-128.
2. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train* 2007; 42(2):311-319.
3. Sepulveda F, Sanchez L, Amy E, et al. Anterior cruciate ligament injury: return to play, function and long-term considerations. *Curr Sports Med Rep* 2017; 16(3):172-178.
4. Carlson VR, Sheehan FT, Boden BP. Video analysis of anterior cruciate ligament (acl) injuries: a systematic review. *JBJS Rev* 2016; 4(11):10.2106/JBJS.RVW.15.00116.

5. Dai B, Garrett WE, Gross MT, et al. The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. *Am J Sports Med* 2015; 43(2):466-474.
6. Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech* 2008; 23(3):313-319.
7. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train* 2008; 43(4):396-408.
8. Dai B, Mao D, Garrett WE, et al. Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs. *J Sport Health Sci* 2014; 3(4):299-306.
9. Leppanen M, Pasanen K, Krosshaug T, et al. Sagittal plane hip, knee, and ankle biomechanics and the risk of anterior cruciate ligament injury: a prospective study. *Orthop J Sports Med* 2017; 5(12):2325967117745487.
10. Leppanen M, Pasanen K, Kujala UM, et al. Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med* 2017; 45(2):386-393.
11. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med* 2009; 43(6):417-422.
12. Stuelcken MC, Mellifont DB, Gorman AD, et al. Mechanisms of anterior cruciate ligament injuries in elite women's netball: a systematic video analysis. *J Sports Sci* 2016; 34(16):1516-1522.

13. Walden M, Krosshaug T, Bjorneboe J, et al. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. *Br J Sports Med* 2015; 49(22):1452-1460.

14. Boden BP, Torg JS, Knowles SB, et al. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *Am J Sports Med* 2009; 37(2):252-259.

15. Sheehan FT, Sipprell WH,3rd, Boden BP. Dynamic sagittal plane trunk control during anterior cruciate ligament injury. *Am J Sports Med* 2012; 40(5):1068-1074.

16. Hinshaw TJ, Davis DJ, Layer JS, et al. Mid-flight lateral trunk bending increased ipsilateral leg loading during landing: a center of mass analysis. *J Sports Sci* in press. doi: 10.1080/02640414.2018.1504616.

17. Dai B, Cook RF, Meyer EA, et al. The effect of a secondary cognitive task on landing mechanics and jump performance. *Sports Biomech* 2017;:1-14.

18. Dai B, Hinshaw TJ, Trumble TA, et al. Lowering minimum eye height to increase peak knee and hip flexion during landing. *Res Sports Med* 2018; 26(3):251-261.

19. Stephenson ML, Hinshaw TJ, Wadley HA, et al. Effects of timing of signal indicating jump directions on knee biomechanics in jump-landing-jump tasks. *Sports Biomech* 2018; 17(1):67-82.

20. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med* 2010; 38(11):2218-2225.

21. Dai B, Mao M, Garrett WE, et al. Biomechanical characteristics of an anterior cruciate ligament injury in javelin throwing. *Journal of Sport and Health Science* 2015; 4(4):333-340.

22. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, Series B* 1995; 57(1):289-300.

23. Cohen J. *Statistical power analysis for the behavioural sciences,* Hillsdale, NJ, Lawrence Erlbaum Associates, 1988.

24. Markolf KL, Burchfield DM, Shapiro MM, et al. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res* 1995; 13(6):930-935.

25. Taylor KA, Terry ME, Utturkar GM, et al. Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. *J Biomech* 2011; 44(3):365-371.

26. Taylor KA, Cutcliffe HC, Queen RM, et al. In vivo measurement of ACL length and relative strain during walking. *J Biomech* 2013; 46(3):478-483.

27. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med* 2007; 35(7):1123-1130.

28. Beardt BS, McCollum MR, Hinshaw TJ, et al. Lower extremity kinematics differed between a controlled drop-jump and volleyball-takeoffs. *J Appl Biomech* 2018; 34(4):327-335.

Figure Captions

Figure 1. The Backward (top), Up (middle), and Forward (bottom) conditions.

Figure 2. Ensemble curves with the 95% confidence interval of the mean for mid-flight upper body (top left), pelvis (top middle), leg (top right) center of mass positions as well as hip (bottom left), knee (bottom middle), and ankle (bottom right) joint positions.

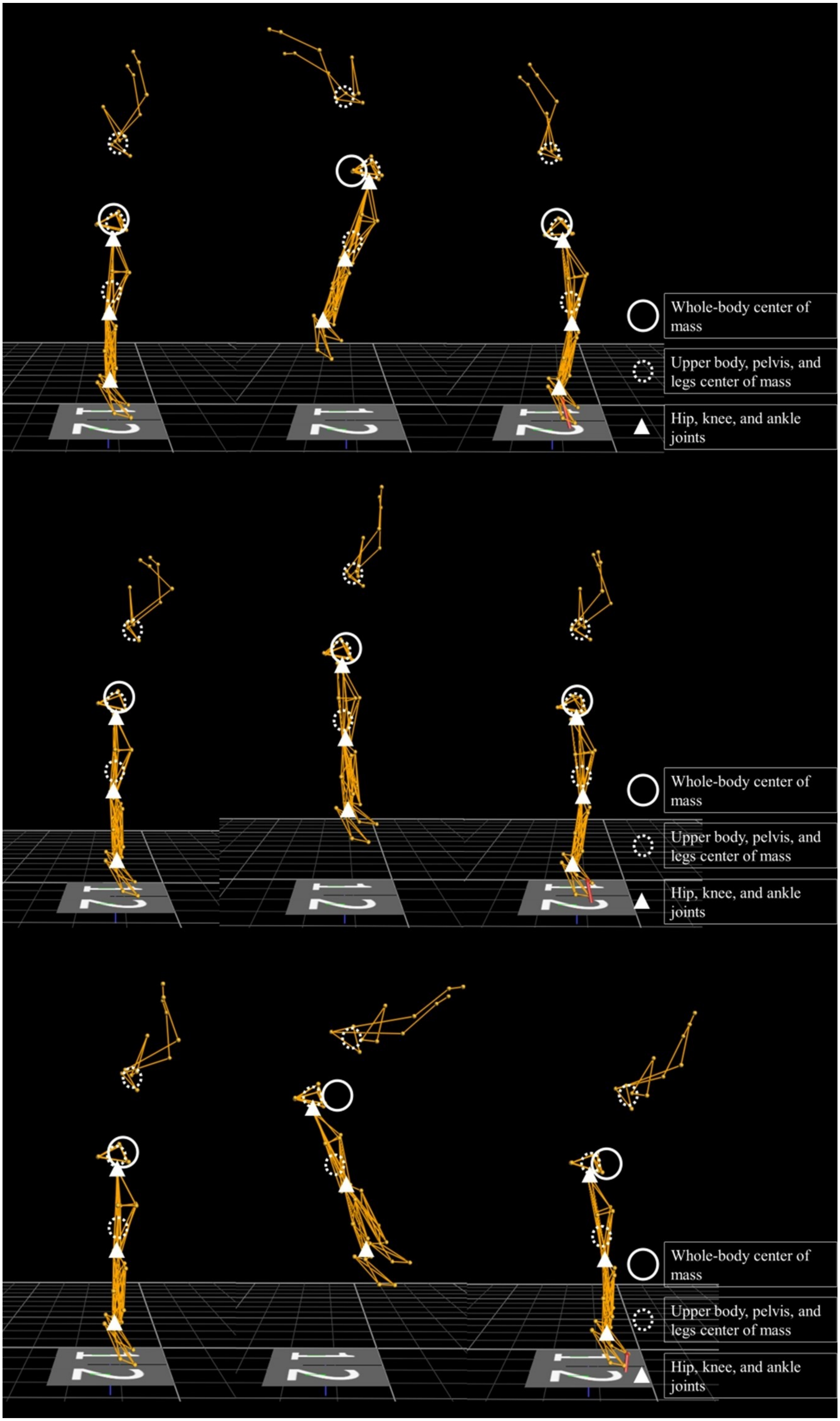
Appendix

Inclusion and Exclusion Criteria

The participants needed to have experience in playing sports that involved jump-landing activities. Sports experience was defined as currently playing sports at least 1 time per week or having previously played at high school, college, or club levels. The participants needed to be physically active, defined as participating in exercise and sports at least two times per week for a total of 2 hours per week. An individual was excluded if he / she (1) had an ACL injury or other major lower extremity injuries which involved surgical treatment. (2) had a lower extremity injury that prevented participation in physical activity for more than 2 weeks over the previous 6 months, (3) possessed any cardiovascular, respiratory, neurologic, or other conditions that prevent him / her from participating at maximal effort in sporting activities, (4) was allergic to adhesive, (5) was pregnant.

Acknowledgement

None.


Whole-body center of mass
Upper body, pelvis, and legs center of mass
Hip, knee, and ankle joints
Whole-body center of mass
Upper body, pelvis, and legs center of mass
Hip, knee, and ankle joints
Whole-body center of mass
Upper body, pelvis, and legs center of mass
Hip, knee, and ankle joints

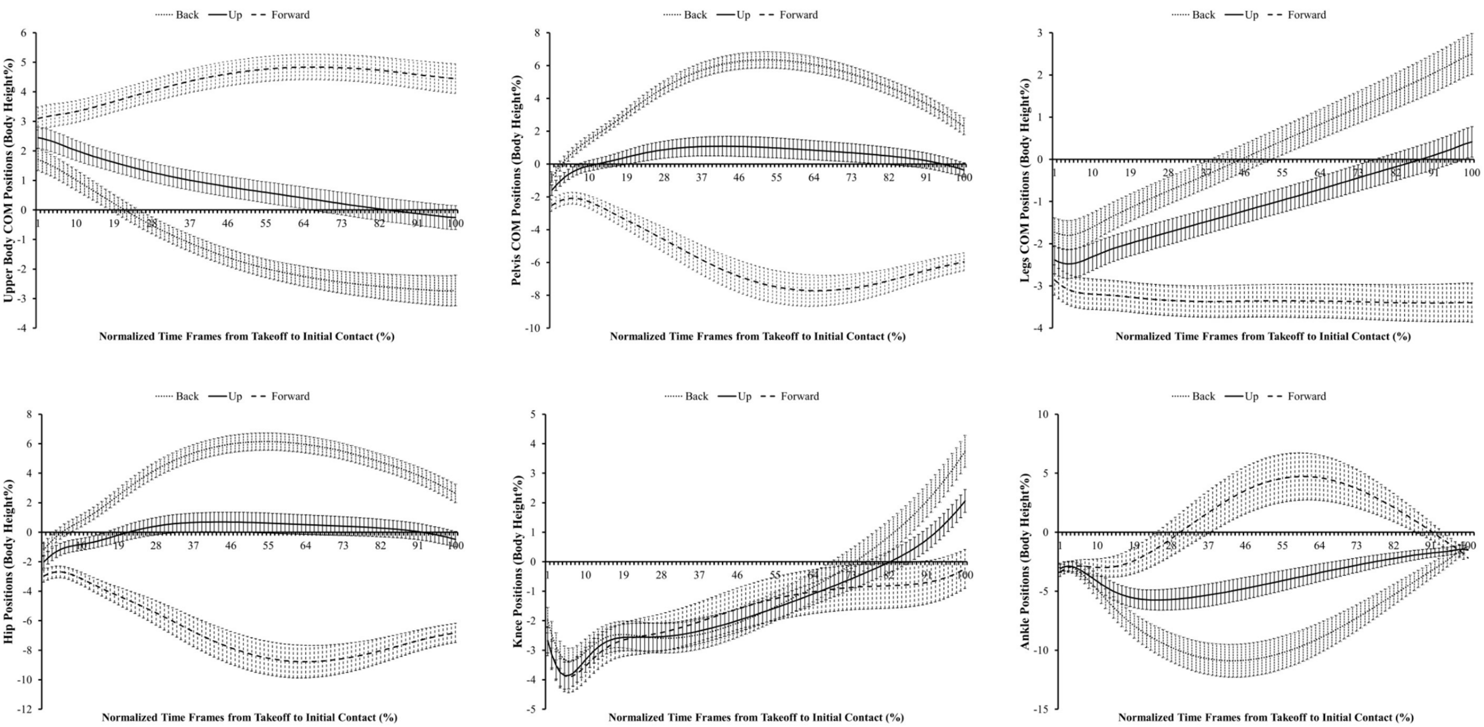

Back
Up
Forward
Upper Body COM Positions (Body Height%)
Pelvis COM Positions (Body Height%)
Legs COM Positions (Body Height%)
Hip Positions (Body Height%)
Knee Positions (Body Height%)
Ankle Positions (Body Height%)
Normalized Time Frames from Takeoff to Initial Contact (%)

Table 1. Mean ± standard deviations of dependent variables and p values of ANOVAs

	Women			Men			p values of ANOVAs		
	Backward	Up	Forward	Backward	Up	Forward	Jump-Landing	Sex	Interaction
Jump Height (m)	0.37 ± 0.07	0.39 ± 0.07	0.36 ± 0.07	0.54 ± 0.06	0.59 ± 0.04	0.53 ± 0.05	**<0.001**	**<0.001**	**0.006**
Upper Body COM Position at Initial Contact (BH %)	-2.59 ± 1.76	-0.06 ± 1.40	4.65 ± 1.36	-2.91 ± 1.65	-0.50 ± 1.24	4.18 ± 1.97	**<0.001**	0.203	0.941
Pelvis COM Position at Initial Contact (BH %)	2.39 ± 1.50	-0.34 ± 1.32	-5.81 ± 1.58	2.18 ± 1.89	-0.39 ± 1.52	-6.15 ± 2.10	**<0.001**	0.579	0.867
Legs COM Position at Initial Contact (BH %)	2.12 ± 1.52	0.17 ± 1.16	-3.37 ± 1.14	2.98 ± 1.58	0.73 ± 1.15	-3.44 ± 1.93	**<0.001**	0.116	0.285
Hip Joint Position at Initial Contact (BH %)	2.61 ± 1.96	-0.58 ± 1.70	-6.79 ± 1.82	2.67 ± 2.21	-0.36 ± 1.74	-6.87 ± 2.54	**<0.001**	0.878	0.890
Knee Joint Position at Initial Contact (BH %)	3.15 ± 1.49	1.71 ± 1.10	-0.08 ± 1.82	4.49 ± 1.86	2.50 ± 1.36	-0.45 ± 2.58	**<0.001**	0.133	0.059
Ankle Joint Position at Initial Contact (BH %)	-1.84 ± 1.79	-1.59 ± 1.06	-1.78 ± 1.11	-0.44 ± 1.59	-1.38 ± 1.20	-2.68 ± 1.77	**0.002**	0.476	**0.001**
Hip Flexion Angles (-) at Initial Contact (°)	-3.52 ± 6.98	-12.8 ± 7.38	-31.9 ± 9.81	-3.07 ± 8.77	-12.7 ± 7.42	-33.9 ± 13.9	**<0.001**	0.814	0.665
Knee Flexion Angles (+) at Initial Contact (°)	14.2 ± 5.11	14.0 ± 5.88	20.9 ± 8.02	14.7 ± 9.80	14.4 ± 9.38	19.1 ± 9.36	**<0.001**	0.897	0.378
Ankle Plantarflexion Angles (+) at Initial Contact (°)	33.4 ± 8.83	37.3 ± 6.11	41.4 ± 5.81	32.9 ± 9.47	33.3 ± 14.0	37.4 ± 10.1	**<0.001**	0.296	0.123
Hip Flexion Angles (-) at 100 ms after Landing (°)	-23.2 ± 17.4	-34.8 ± 16.7	-55.0 ± 11.1	-23.7 ± 16.8	-35.7 ± 13.2	-60.1 ± 19.5	**<0.001**	0.496	0.622
Knee Flexion Angles (+) at 100 ms after Landing (°)	56.4 ± 10.3	57.6 ± 9.07	63.2 ± 9.71	59.3 ± 12.0	62.3 ± 11.2	63.8 ± 11.7	**<0.001**	0.394	0.091
Ankle Dorsiflexion Angles (-) at 100 ms after Landing (°)	-27.0 ± 5.29	-25.0 ± 4.77	-19.8 ± 4.82	-27.1 ± 5.63	-26.0 ± 5.18	-18.0± 8.66	**<0.001**	0.888	0.214

Peak Vertical GRF within 100 ms after Landing (BW)	3.44 ± 0.75	3.54 ± 0.86	3.64 ± 0.83	5.04 ± 1.69	5.39 ± 1.55	5.38 ± 1.59	**0.027**	0.493	**<0.001**
Peak Posterior GRF within 100 ms after Landing (BW)	0.89 ± 0.27	0.62 ± 0.22	0.45 ± 0.21	1.06 ± 0.21	0.97 ± 0.17	0.69 ± 0.20	**<0.001**	**<0.001**	0.056
Peak Knee Extension Moments (-) within 100 ms after Landing (BW*BH)	-0.12 ± 0.03	-0.10 ± 0.02	-0.07 ± 0.02	-0.17 ± 0.04	-0.15 ± 0.03	-0.11 ± 0.03	**<0.001**	**<0.001**	0.292
Average Knee Extension (-) / Flexion Moments (+) within 100 ms after Landing (BW*BH)	-0.06 ± 0.01	-0.05 ± 0.01	-0.03 ± 0.02	-0.08 ± 0.02	-0.07 ± 0.02	-0.05 ± 0.02	**<0.001**	**<0.001**	0.244
Peak Hip Flexion Moments (-) within 100 ms after Landing (BW*BH)	-0.19 ± 0.06	-0.13 ± 0.05	-0.09 ± 0.04	-0.25 ± 0.08	-0.21 ± 0.04	-0.15 ± 0.04	**<0.001**	**<0.001**	0.125
Average Hip Extension (+) / Flexion (-) Moments within 100 ms after Landing (BW*BH)	-0.02 ± 0.02	-0.01 ± 0.01	0.02 ± 0.01	-0.03 ± 0.02	-0.01 ± 0.02	0.03 ± 0.03	**<0.001**	0.439	0.335
Peak Knee Varus Moments (+) within 100 ms after Landing (BW*BH)	0.05 ± 0.02	0.03 ± 0.01	0.03 ± 0.01	0.06 ± 0.03	0.05 ± 0.02	0.04 ± 0.01	**<0.001**	**0.030**	0.705
Peak Knee Valgus Angles (-) within 100 ms after Landing (°)	-1.21 ± 3.49	-0.67 ± 3.34	-0.69 ± 4.44	-3.57 ± 2.97	-2.94 ± 2.67	-2.73 ± 3.70	0.064	0.041	0.793

Note: COM: center of mass; BH: body height; Center of mass and joint position of each component was relative to whole-body center of mass position in the anterior (+) / posterior (-). GRF: ground reaction force; BW: body weight; BH: body height