Research Paper

Hong Kong Physiotherapy Journal
https://www.worldscientific.com/worldscinet/hkpj

Reliability of three-dimensional motion analysis during single-leg side drop landing test after anterior cruciate ligament reconstruction: An *in vivo* motion analysis study

Johnson Chun Yiu Pang[1,*] and Rachel Suet Wai Tsang[2,†]

[1]*School of Health Sciences, Caritas Institute of Higher Education*
2 Chui Ling Lane, Tseung Kwan O, N.T., HKSAR, China

[2]*Shatin Hospital, Hospital Authority, 33 A Kung Kok Street*
Ma On Shan, Shatin, NT, HKSAR, China

*jpang@cihe.edu.hk
†rachelxmail@gmail.com

Background: Anterior cruciate ligament (ACL) injury is a common sport injury and investigation of landing biomechanics is helpful in injury prevention and rehabilitation. Recent study found a lateral single-leg drop landing test resulted in the highest peak knee valgus angle (PKVA), but its reliability on patients who received ACL reconstruction (ACLR) is unknown.

Objective: This study aimed to investigate the reliability in both within and between days on the normalized vertical ground reaction force (NVGRF) and kinematics of lower limbs after receiving ACLR. The findings can form the cornerstone for further study related to lateral jumping-and-landing biomechanics in patients with ACLR.

Methods: This was a test-retest reliability study. Twelve patients (four females and eight males) who received ACLR with mean age of 29.4 (SD $\pm$ 1.66) were recruited. The subjects were instructed to jump laterally from 30 cm height and landed with single-leg for five times. The procedure was conducted on both legs for comparison. The NVGRF and local maxima of the hip, knee and ankle angles during the first 100 ms in all three planes were analyzed. The measurement was conducted by the same assessor to evaluate the within-session reliability, and the whole procedure was repeated one week later for the evaluation of the

*Corresponding author.

between-session reliability. Intra-class correlation coefficient (ICC) test was used to assess the within- and between-session reliability by ICC (3, 1) and ICC (3, K) respectively.

Results: The within-session reliability of NVGRF [ICC (3, 1)] was 0.899–0.936, and its between-session reliability [ICC (3, K)] was 0.947–0.923. Overall reliability for kinematics within-session [ICC (3, 1)] was 0.948–0.988, and the between-session reliability [ICC (3, K)] was 0.618–0.982, respectively. Good to excellent reliability for the lateral single-leg drop landing test was observed in most of the outcome measures for within- and between-session. The ICC value of NVGRF of ACLR leg was lower than that of the good leg in the within-session which may associate with lower neuromuscular control in ACLR leg than that of the good leg.

Conclusion: The results of this study support the use of a lateral single-leg drop landing test to evaluate lower limb biomechanics for ACLR.

Keywords: 3D Motion Analysis; Anterior Cruciate Ligament Reconstruction; Drop Landing Test; Kinematics; Reliability.

Introduction

Anterior cruciate ligament (ACL) injury is one of the most common sport injuries.[1] The incidence rate of ACL injuries through a non-contact manner is around 70%.[2–4] Excessive knee valgus,[5] and knee outward rotation coincidence with hip internal rotation,[6] in particular, during one leg landing[7] are proposed to be the injury mechanisms. Non-contact ACL injuries may occur within the first 40 mini-seconds (ms) from foot-contact to the ground in landing[8] and injury may occur approximately at the timing of the peak vertical ground reaction forces (VGRF),[9] and closely associated with the ACL injury.[10] Therefore, a soft-landing to decrease the VGRF by increasing hip and knee flexion angles during landing has been deemed as one of the re-injury prevention training programs. Landing biomechanics is thereby one of the concerns for injury prevention and rehabilitation.

Three-dimensional (3-D) motion analysis has been widely used as a tool for clinical evaluation and research on the ACL injury. Drop vertical jump (DVJ) landing[11] and stop jump (SJ) landing[12] have been used to assess the jumping performance of athletics landed mainly in the sagittal plane. More recently, single-leg jump landing in lateral direction was suggested.[13,14] The lateral single-leg landing resulted in the highest peak knee valgus angle (PKVA) compared to jump in a forward and diagonally at 30° and 60°.[15] A higher risk of knee injury might occur during lateral jump landing than forward and diagonal directions, and significantly influenced ($P < 0.05$) muscle activities of vastus lateralis, rectus femoris and semitendinosus.[16] Indeed, lateral single-leg drop landing test has been used in some jump-landing

studies.[11,15,17–19] Measures of 3-D motion analysis should be population-specific as the characteristics of the specific pathology or after undergoing operation such as anterior cruciate ligament reconstruction (ACLR) that may affect the biomechanics of lower limbs. More importantly, the repeatability of the single-leg landing test in a lateral direction for patients who received ACLR is unknown. Before a test can be adopted in clinical practice, in particular, in assessing the treatment effects at two different time points, the test needed to have good repeatability. It is our intent in investigating the test-retest reliability of the single-leg drop landing test in lateral direction on subjects with ACLR.

The purpose of this study was to determine the test–retest reliability of within-session and between-session of the normalized vertical ground reaction force (NVGRF) and kinematics of the hip, knee and ankle during lateral single-leg drop landing test on patients with ACLR. We set the hypothesis that the impact force and joint motions of the hip, knee and ankle would achieve good to excellent within and between days repeatability.

Methods

Participants

The study design was to assess the test–retest reliability of a lateral single-leg drop landing test in patients with ACLR after 6-month rehabilitation. Twelve patients (four females and eight males) who received ACLR with mean age 29.4 (SD ± 1.66), weight 68.3 kg (SD ± 5.13), height 170.4 cm (SD ± 2.54) and post-ACLR 10.0 months (SD ± 0.85) were recruited. The subjects who completed the full course of physiotherapy training including

DVJ landing techniques were included. Subjects were excluded if they had other major lower extremity injuries or surgeries, such as anterior knee pain or general joint laxity. A list of subjects was generated by computer randomized program after screening with the inclusion and exclusion criteria. The procedure was conducted by an independent research assistant who did not otherwise involve in the trial and did not participate in analysis or interpretation of the results. The allocation sequence of NVGRF and kinematics measurement and interpretation were concealed from the principal investigator, who measured all the subjects in a blinded manner. Each participant's allocation was contained in sequentially numbered sealed and stapled opaque envelopes. It was then handled by the independent research assistant who was not available for the process of capture and graph interpretation. The group allocation and data were concealed in a password-protected computer file only accessible by the independent research assistant. Ethics committee approval was obtained from the Joint Chinese University of Hong Kong New Territories East Cluster Clinical Research Ethics Committee. Informed written consent was obtained from each subject before the test. The trial was conducted in accordance with the Declaration of Helsinki.

Procedure

The study was conducted in the motion analysis laboratory at the Physiotherapy Department, PWH where equipped with a Vicon™ system and Bonita™ camera system (Oxford Metrics, Oxford, United Kingdom) and a multicomponent force plate (Bertec Corporation, Columbus, United States of America). The tester (the principal investigator) was a post-graduate trained physiotherapist with over 20 years clinical experience and received 3-D motion analysis training program. Kinematic data were captured by ten cameras at sampling frequency of 100 Hz. Sixteen 14 mm reflective markers, according to lower body model of Plug-in-Gait, were placed bilaterally on the subject's bony prominence at the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), thigh, lateral condyles of femur (1.5 cm above the mid-point of lateral knee joint line), shank, lateral malleolus, heel and second metatarsals by double-sided adhesive tapes. A 30 cm height wooden platform was placed at a distance of

Fig. 1. Subjects using single-leg side drop landing from a 30 cm height wooden platform.

20 cm from the center of the force plate. The ground reaction forces (GRFs) were captured at a sampling rate of 1,000 Hz. After five-minute moderate intensity warm-up on a cycle ergometer, subjects were instructed to practice 3–5 times lateral single-leg drop landing with a sub-maximal effort to familiarize the testing movement. The participants stood on a wooden platform, single-legged and bared-foot. The non-weight-bearing leg was kept in 90° of knee flexion and with a neutral hip rotation; both hands were placed on the waist to eliminate variability in jumping mechanics due to arm swing (Fig. 1). Subjects were instructed to jump off the wooden platform in a lateral direction without an upward jump action and landed with ankle in a neutral position while facing and looking forward during the drop landing tests. The trial was regarded as unsuccessful if the subjects could not maintain their balance upon landing, land beyond the force plate, or be unable to keep hands on the waist. A total of five successful trials with 30-s rest in-between were captured for offline analysis, and both non-operated and ACLR legs were assessed. The procedure was repeated one week later for the assessment of between-day reliability. To eliminate the error from the placement of the reflective markers between these two assessment days, an approach of strictly referenced static alignment was used based on the anatomical coordinate system (ACS).[20] In addition, the Modified Cincinnati Rating System Questionnaire (MCRSQ) was used to evaluate the current knee functions of the subjects with a score of 100 totally.

Data collection

The images captured from the Vicon system were filtered by a fourth-order zero-lag Butterworth
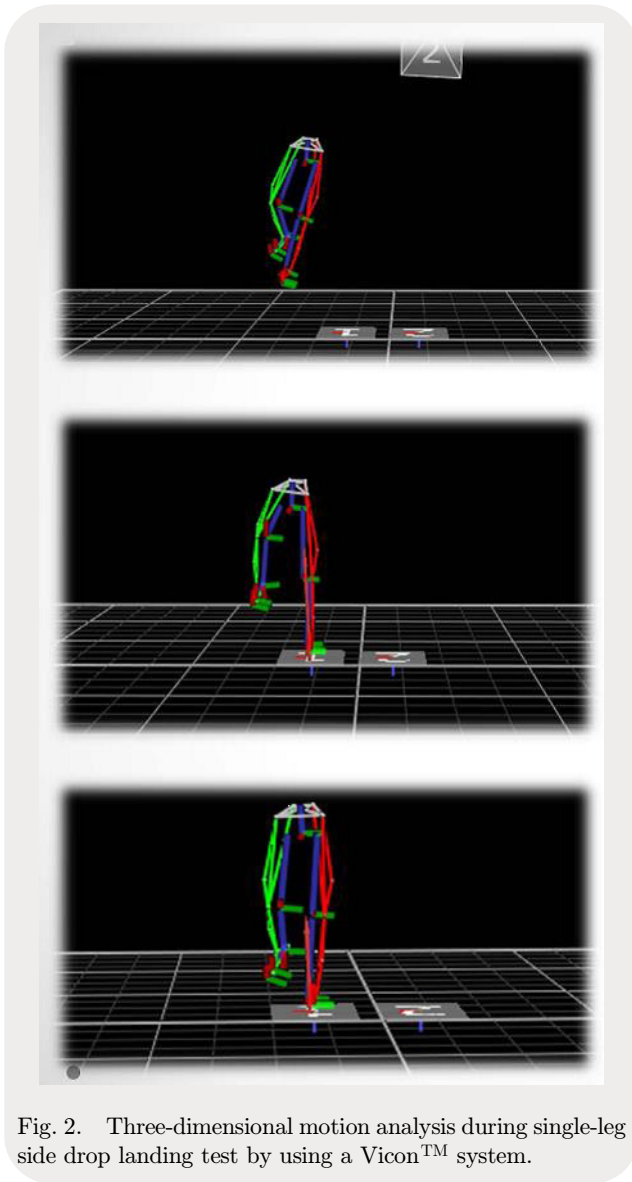
Fig. 2.   Three-dimensional motion analysis during single-leg side drop landing test by using a Vicon™ system.

digital filter at a cut-off frequency of 12 Hz residual analysis technique.[11,21] In order to define initial contact (IC), VGRF was used to identify the time of IC with the ground immediately after the subject dropped from the box. IC was defined when VGRF first exceeded 10 N.[11] Because the risk of injury was believed to be highest during the initial landing, only the first 100 ms of the contact phase was used for the analysis of kinematic parameters.[3,22] The peak VGRF and local maxima of the hip, knee and ankle angles during the first 100 ms in all three planes were analyzed by calculating the marker trajectories with the Vicon Nexus (Nexus version 1.8.5) (Fig. 2) and Polygon software (Polygon version 3.5.2, Oxford Metrics, Oxford, UK). The mean values of five trials for each subject were used for statistical evaluation.

The peak VGRF data were normalized to body weight and become the NVGRF. To avoid bias, all the kinetics and kinematics analyses were done in a blinded fashion by the first investigator. The statistics analysis was done by an independent research assistant who did not otherwise involve in the trial and did not participate in the interpretation of the NVGRF and kinematics of the subjects.

Statistical analysis

Sample size calculation: Based on previous studies,[11,12,20] we estimated there would be an average value of intraclass correlation coefficients (ICC) around 0.75 for the reliability of within-session and between-sessions. A sample size of 12 would be able to detect a true difference in ICC between the null and alternative hypothesis with 80% power, with Alpha error of 0.05.[23] Similar sample size was used in previous reliability studies similar to this study.[11,12] Intra-class correlation coefficient (ICC) test was used to evaluate the test-retest reliability of the discrete variables within- [ICC (3,1)] and between-sessions [ICC (3, k)], and used absolute agreement, with ≥ 0.75 considered 'good' and ≥ 0.90 considered excellent.[24] Intention-to-treat analysis was considered for defaulted subjects.

Results

Twelve subjects completed the study without any dropout, and the results are summarized in Tables 1–3. The findings from this study indicated good to excellent test–retest reliability on the maximal joint angles and NVGRF measures during the lateral single-leg drop landing test on the

Table 1.   Within session and between sessions measurements of the reliability of normalized vertical ground reaction force for both non-operated leg and ACLR leg during single-leg side drop landing test.

NVGRF (% of BW*)	Within session ICC (3,1)		Between-session ICC (3,k)	
	Present study	Milner et al., 2011	Present study	Milner et al., 2011
Non-operated leg	0.936	0.849	0.923	0.829
ACLR leg	0.889	—	0.947	—

Note: *BW=body weight.

Table 2.   Within-session measurements of reliability of kinematics for both non-operated leg and ACLR leg during single-leg side drop landing test.

Joint Angle (degree)	Within-session ICC (3,1)		Ford et al. (2007) DVJ of both legs
	Present study		
	ACLR leg	Non-operated leg	
Hip Flexion	0.981	0.977	0.956
Hip Adduction	0.961	0.948	0.712
Hip Internal Rotation	0.988	0.974	0.934
Knee Flexion	0.965	0.986	0.933
Knee Abduction	0.978	0.969	0.993
Knee Internal Rotation	0.979	0.989	0.971
Ankle Dorsiflexion	0.948	0.965	0.955
Ankle Eversion	0.983	0.956	0.966
Ankle Abduction	0.978	0.987	—

Table 3.   Between-sessions measurements of reliability for both non-operated leg and ACLR leg during single-leg side drop landing test.

Joint Angle (degree)	Between-session ICC (3,k)		Ford et al. (2007) DVJ of both legs
	Present study		
	ACLR leg	Non-operated leg	
Hip Flexion	0.892	0.884	0.595
Hip Adduction	0.887	0.905	0.791
Hip Internal Rotation	0.847	0.766	0.699
Knee Flexion	0.902	0.982	0.616
Knee Abduction	0.826	0.895	0.855
Knee Internal Rotation	0.725	0.870	0.872
Ankle Dorsiflexion	0.876	0.841	0.922
Ankle Eversion	0.668	0.618	0.835
Ankle Abduction	0.812	0.853	—

Table 4.   Within-session measurements of reliability of kinematics for both non-operated leg and ACLR leg during single-leg side drop landing test before and after using the approach of subtraction of the peak joint angles to the initial angles from static capture.

Joint Angle (degree)	Between-session ICC (3,k)			
	Before subtraction		After subtraction	
	ACLR leg	Non-operated leg	ACLR leg	Non-operated leg
Hip Flexion	0.893	0.918	0.981	0.977
Hip Adduction	0.799	0.814	0.961	0.948
Hip Internal Rotation	0.945	0.956	0.988	0.974
Knee Flexion	0.876	0.918	0.965	0.986
Knee Abduction	0.852	0.904	0.978	0.969
Knee Internal Rotation	0.937	0.961	0.979	0.989
Ankle Dorsiflexion	0.838	0.811	0.948	0.965
Ankle Eversion	0.921	0.860	0.983	0.956
Ankle Abduction	0.911	0.907	0.978	0.987

Table 5. Between-sessions measurements of reliability for both non-operated leg and ACLR leg during single-leg side drop landing test before and after using the approach of subtraction of the peak joint angles to the initial angles from static capture.

| | Between-session ICC (3,k) | | | |
| | Before subtraction | | After subtraction | |
Joint Angle (degree)	ACLR leg	Non-operated leg	ACLR leg	Non-operated leg
Hip Flexion	0.901	0.801	0.892	0.884
Hip Adduction	0.300	0.741	0.887	0.905
Hip Internal Rotation	0.755	0.735	0.847	0.766
Knee Flexion	0.934	0.963	0.902	0.982
Knee Abduction	0.738	0.936	0.826	0.895
Knee Internal Rotation	0.750	0.901	0.725	0.870
Ankle Dorsiflexion	0.874	0.732	0.876	0.841
Ankle Eversion	0.363	0.546	0.668	0.618
Ankle Abduction	0.594	0.830	0.812	0.853

ACLR and non-operated legs (ICC = 0.889–0.947), except hip internal rotation (ICC = 0.766) and ankle eversion showed (ICC = 0.618) in the good leg; and knee internal rotation (ICC = 0.725) and ankle eversion (ICC = 0.668) showed good reliability in ACLR leg.

The ICC values of NVGRF and kinematics within-session were higher than between-session, except the ACLR leg in NVGRF within-session was 0.899 slightly lower than between-session was 0.947.

In general, the values of ICC for the kinematic data of hip, knee and ankle in frontal and transverse plane were lower than sagittal plane showed in between-session. Tables 4 and 5 showed the comparison of the values of ICC for within and between days before and after using the approach of subtraction of the peak joint angles to the baseline angles from static capture. Most of the ICC values were higher after using the approach which could offset the error from the baseline values of the joint angles measured in static capture.

Discussion

The aim of this study is to determine the reliability of lateral single-leg drop landing test within and between sessions for patients with ACLR. Findings from this study indicated that the joint kinematics have good to excellent test–retest reliability in both the reconstructed and non-operated leg in the patients with ACLR.

Our findings suggested that the ICC values of hip, knee and ankle in within-session are higher than that in between-session. Similar pattern has been reported by other investigators during gait,[25,26] Jogging[20,27] and DVJ,[11] that within-session repeatability is higher than between-session. Multiple factors may cause these errors including marker-placement errors, referenced static alignment, task difficulty, and neuromuscular control.[11] It has been reported that ground reaction force variable is the sum of all the segmental masses and accelerations and gravitational force,[20] which is less influenced by marker placement; therefore giving robust support in the way the subjects landed from the lateral single-leg drop jump showing the source of variability within the session of measurement. The ICC value of NVGRF of ACLR leg is lower than that of good leg in the within-session which may indicate the neuromuscular control for ACLR leg is lower. Our findings echo with the evidence that the risk factors related to second ACL injury are closely related to previous neuromuscular impairments.[28]

The result of this study supports that the reliability of NVGRF is ranged from ICC = 0.899–0.936 for within-session measurement, and is higher than the previous study reported by Milner *et al.* (2011), which the ICC reported was 0.849 for the SJ.[12] Our study also finds that the reliability of the NVGRF for the between-session measurement maintains with the range of ICC from 0.923–0.947 (Table 2). This suggests that the intra-subject variability of lateral single-leg landing test is lesser

than SJ and suitable for cross-sectional and longitudinal studies. It may be related to the complexity of the action for the lateral single-leg drop landing test which is lesser than SJ. As compared with the data of hip flexion and knee flexion of DVJ in between-days reported by Ford *et al.*,[11] the ICC value of our study is much higher (Table 3). It may be related to the complexity of DVJ that required the subjects to do maximum vertical jump before landing, and the subjects may vary in the maximum effort which may be relatively more dangerous for patients than single-leg drop landing test. In our current study, the procedure of lateral single-leg drop landing test does not require the participants to do maximum vertical jump which should be safer for ACLR patients in a more reliable manner as compared with DVJ.

In general, reliability between-session measurement for the sing-leg drop landing test is similar to that found in within-session and achieved good to excellent repeatability. The ICC value of kinematic data for the hip, knee joints of good leg are higher than those reported by Ford *et al.*,[11] while that is not necessarily the same for ACLR leg in knee abduction and in knee internal rotation. Both of them have shown lower ICC value. Previous reliability studies on landing mainly focus on athletes who had not suffered an ACL injury or underwent reconstruction surgery.[11,12] Their findings may not be able to generalize to the population who received ACLR surgery, especially the knee movements in frontal and transverse planes. In this study, we found that the reliability of knee internal rotation for ACL leg was much lower than the good leg in between-session. It indicated that the influence of ACLR surgery and rehabilitation cannot be neglected in the interpretation of findings in longitudinal studies. Moreover, the ICC values of ankle eversion for ACLR and good leg in between-session measurement are both lower than within-session measurement significantly, therefore precaution should be taken if a lateral single-leg drop landing test is used to investigate the kinematics of the ankle joint in frontal plane. This may not be related to the surgery of ACLR as the good leg has also shown lower reliability in between-session measurement; this variability may be related to the placement of markers producing an offset shift. Then the data may result in lower between-day reliability. It may also be related to cross-talk between the planes of motion and the direction of lateral jump and landing required more demanding on the stability to the ankle joint in

frontal plane causing greater neuromuscular variability. Concerning the reliability of frontal planes and transverse plane, it has been reported by Ramakrishnan and Kadaba[29] that the sensitivity analysis to examine the errors contributing to incorrectly defining the embedded axes at the hip and knee during the gait motion analysis, especially abduction–adduction and internal–external rotations axes, which have attributed to cross-talk. These measurement errors may be minimized by standardization of markers placement with an experienced single investigator, using standardized posture and foot placement.[11,30]

Based on our clinical experience, calibration of the system before the start of every trial can effectively minimize the error from noise signal or even any reflection from the change of environmental factors. To minimize measurement error, some crucial points should be considered such that the performance of the subjects should be consistent. Clear and standardized instruction and warm-up trials are useful to let the subjects understand and perform consistently during the trials. The complexity of landing test would contribute to the error of subject's performance that should be under consideration. Clinically, the body-build of subjects can be attributed as a source of error, especially over a big tummy, which will affect the location of the bony landmark of ASIS. The skin movement and artifact of soft tissues will limit the accurate estimation of segmental kinematics.[31] To reduce the error of 3D motion analysis, it is necessary to avoid placement of markers over large muscle mass, further modification of measurement technique is necessary. The current model of measurement heavily depends on the skill of assessors in accurately placing markers. A rigorous referenced static alignment is following the ACS protocol.[20] The assessor must keep the initial joints angles in static capture close to anatomical zero as much as possible and the angle of between the proximal segment and distal segment is close to zero, then under this condition, the approach of subtraction to the value of peak joint angle from the initial joint angle can be used so as to eliminate the error from the placement of markers, the actual change of the joints angles during lateral single-leg drop landing test can be measured, and the reliability between the two examination days can be generally improved (Tables 4 and 5). Filter strategy is useful in this study to minimize error from noise signal and enhance the reliability of the lateral single-leg drop landing test.

Conclusions

The lateral single-leg drop landing test is reliable to evaluate 3-D motion biomechanics during landing in longitudinal studies for the patients who received ACLR with a repeated measure design. It may be useful in clinical practice, and it also provides a scientific basis for further study in injury prevention program and the potential to serve as a screening test giving recommendation to the physician on whether the patients is fit for return-to-sport.

Conflict of Interest

The authors (Johnson Chun Yiu, PANG and Rachel Suet Wai) have no conflict of interest relevant to this paper.

Funding/Support

Author Contributions

Conception and design of the study was made by Johnson Chun Yiu, PANG, Rachel Suet Wai, TSANG; analysis and/or interpretation of data were made by Johnson Chun Yiu, PANG, Rachel Suet Wai, TSANG; drafting the paper was made by Johnson Chun Yiu, PANG, Rachel Suet Wai, TSANG; revising the paper critically for important intellectual content was made by Johnson Chun Yiu, PANG. Both authors were involved in the approval of the paper to be published.

Acknowledgments

References

1. Griffin LY, Agel J, Albohm MJ, Arendt EA, Dick RW, Garrett WE et al. Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. J Am Acad Orthop Surg 2000;8:141–150.
2. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. Am J Sports Med 1995;23:694–701.
3. Boden BP, Dean GS, Feagin JA, Jr., Garrett WE, Jr., Mechanisms of anterior cruciate ligament injury. Orthopedics 2000;23:573–578.
4. Arendt EA, Bershadsky B, Agel J. Periodicity of noncontact anterior cruciate ligament injuries during the menstrual cycle. J Gend Specif Med 2002;5:19–26.
5. Griffin LY, Albohm MJ, Arendt EA, Bahr R, Beynnon BD, Demaio M, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: A review of the Hunt Valley II meeting, January 2005. Am J Sports Med 2006;34:1512–1532.
6. Bencke J, Curtis D, Krogshede C, Jensen LK, Bandholm T, Zebis MK. Biomechanical evaluation of the side-cutting manoeuvre associated with ACL injury in young female handball players. Knee Surg Sports Traumatol Arthrosc 2013;21:1876–1881.
7. Tillman MD, Hass CJ, Brunt D, Bennett GR. Jumping and landing techniques in elite women's volleyball. J Sports Sci Med 2004;3:30–36.
8. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L 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;38:2218–2225.
9. Cerulli G, Benoit D, Lamontagne M, Caraffa A, Liti A. *In vivo* anterior cruciate ligament strain behaviour during a rapid deceleration movement: Case report. Knee Surg Sports Traumatol Arthrosc 2003;11:307–311.
10. Yu B, Lin C-F, Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. Clin Biomech 2006;21:297–305.
11. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: Implications for longitudinal analyses. Med Sci Sports Exerc 2007;39:2021–2028.
12. Milner CE, Westlake CG, Tate JJ. Test–retest reliability of knee biomechanics during stop jump landings. J Biomech 2011;44:1814–1816.
13. Aizawa J, Ohji S, Koga H, Masuda T, Yagishita K. Correlations between sagittal plane kinematics and landing impact force during single-leg lateral jump-landings. J Phys Therapy Sci 2016;28:2316–2321.
14. Aizawa J, Hirohata K, Ohji S, Ohmi T, Yagishita K. Limb-dominance and gender differences in the

ground reaction force during single-leg lateral jump-landings. J Phys Therapy Sci 2018;30:387–392.

15. Sinsurin K, Vachalathiti R, Jalayondeja W, Limroongreungrat W. Altered peak knee valgus during jump-landing among various directions in basketball and volleyball athletes. Asian J Sports Med (AsJSM) 2013;4:195.

16. Sinsurin K, Vachalathiti R, Jalayondeja W, Limroongreungrat W. Knee muscular control during jump landing in multidirections. Asian J Sports Med (AsJSM). 2016;7.

17. King E, Richter C, Franklyn-Miller A, Daniels K, Wadey R, Moran R et al. Whole-body biomechanical differences between limbs exist 9 months after ACL reconstruction across jump/landing tasks. Scand J Med Sci Sports 2018;28:2567.

18. Leporace G, Vianna M, Metsavaht L, Tannure M. 227 Variables associated to knee valgus in male soccer players during a single leg vertical landing task. Brit J Sports Med 2020;54:A94.

19. Teng PSP, Leong KF, Kong PW. Influence of foot-landing positions at initial contact on knee flexion angles for single-leg drop landings. Res Quar Exercise Sport. 2019:1.

20. Ferber R, McClay Davis I, Williams DS, 3rd, Laughton C. A comparison of within- and between-day reliability of discrete 3D lower extremity variables in runners. J Orthop Res 2002;20:1139–1145.

21. Bisseling RW, Hof AL. Handling of impact forces in inverse dynamics. J Biomech 2006;39:2438–2444.

22. Krosshaug T, Slauterbeck JR, Engebretsen L, Bahr R. Biomechanical analysis of anterior cruciate ligament injury mechanisms: Three-dimensional motion reconstruction from video sequences. Scand J Med Sci Sports 2007;17:508–519.

23. Machin D, Campbell MJ, Tan SB, Tan SH. Sample Size Tables for Clinical Studies. Oxford, UK: Wiley-Blackwell, 2009.

24. Portney L. Foundations of Clinical Research Applications to Practice. 4th ed. Philadelphia: F.A. Davis, 2020.

25. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 1989;7:849–860.

26. Steinwender G, Saraph V, Scheiber S, Zwick EB, Uitz C, Hackl K. Intrasubject repeatability of gait analysis data in normal and spastic children. Clin Biomech 2000;15:134–139.

27. Queen RM, Gross MT, Liu H-Y. Repeatability of lower extremity kinetics and kinematics for standardized and self-selected running speeds. Gait Posture 2006;23:282–287.

28. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. J Orthop Sports Phys Ther 2013;43:777–A711.

29. Ramakrishnan HK, Kadaba MP. On the estimation of joint kinematics during gait. J Rehabil Res Develop 1992;29:110.

30. McGinley JL, Baker R, Wolfe R, Morris ME. The reliability of three-dimensional kinematic gait measurements: A systematic review. Gait Posture 2009;29:360–369.

31. Leardini A, Chiari L, Della Croce U, Cappozzo A. Human movement analysis using stereo-photogrammetry. Part 3. Soft tissue artifact assessment and compensation. Gait Posture 2005;21:212–225.