Anterior－Posterior Center of Pressure Is Associated With Knee Extensor Moment During Landing After Anterior Cruciate Ligament Reconstruction

（膝前十字靭帯再建術後患者における着地動作時の足圧中心前後位置は膝関節伸展モーメントと関連する）

申請者：　弘前大学大学院医学研究科 機能再建・再生科学領域
リハビリテーション医学教育研究分野

氏名：　千 々 松　雅 人

指導教授：　津 田　英 一

Abstract

Context

A reduced knee extensor moment (KEM) in the surgical limb and asymmetry in the KEM during landing tasks are observed in patients following anterior cruciate ligament reconstruction (ACLR). There is limited information about the association of kinetic and kinematic parameters with the KEM during landing after ACLR. This study investigated the association of the anterior-posterior center of pressure (anterior–posterior COP) position, vertical ground reaction force (VGRF), and lower limb joint angles with the KEM during landing in female athletes following ACLR.

Methods

Twenty-two female athletes who underwent ACLR performed a drop vertical jump at 7.9 ± 1.7 months after surgery. Three-dimensional motion analysis system equipped with force plates was used to evaluate the KEM, anterior–posterior COP position, VGRF, and sagittal plane hip, knee, and ankle angles.

Results

The subjects had a smaller peak KEM in the surgical limb than in the non-surgical limb during landing (1.43 ± 0.33 Nm/kg/m vs. 1.84 ± 0.41 Nm/kg/m, *P* = .001). The subjects demonstrated a smaller VGRF in the surgical limb than in the non-surgical limb (11.9 ± 2.3 N/kg vs. 14.6 ± 3.5 N/kg, *P* = .005). The limb symmetry index of the KEM was predicted by that of the VGRF

($P < .001$, $R^2 = .621$, β =.800). The KEM was predicted by the anterior–posterior COP position in the surgical limb ($P = .015$, $R^2 = .227$, β =.513) and by the VGRF in the non-surgical limb ($P = .018$, $R^2 = .213$, β =.500). No significant correlation was noted between the KEM and the lower limb joint angles.

Conclusions

The anterior–posterior COP position and VGRF were associated with the KEM during landing. Evaluating the anterior–posterior COP position and VGRF, not the lower limb joint angles, may contribute to understanding the KEM during double-leg landing after ACLR in a clinical setting.

Keywords

Biomechanics, Symmetry, Second injury, Rehabilitation, Motor control

Anterior cruciate ligament reconstruction (ACLR) is a common procedure for ACL injuries, particularly in recreational and competitive athletes.[1] The procedure has good postoperative outcomes, with a reduced anterior knee laxity close to that of an intact knee and improved patient-reported outcomes.[2,3] However, 23% of young athletes who return to sports after ACLR suffer from secondary ACL injuries either to the ipsilateral or contralateral limb.[4] Several prospective cohort studies have identified the modifiable risk factors for secondary ACL injuries after ACLR.[5–7] However, consensus regarding these risk factors has not been established.[8] Secondary ACL injuries in athletes after ACLR is predicted by the asymmetry in the knee extensor moment (KEM) during landing.[5] In addition, asymmetry in KEM has been observed at the time of return to sports and for up to 3 years after ACLR.[9–11] Therefore, there is an increased focus on improving asymmetry in KEM for the prevention of secondary ACL injuries.[12]

Evaluating the KEM during landing tasks is challenging in the clinical setting because an expensive 3-dimensional motion analysis system is required for data collection and analysis. Additionally, 3-dimensional motion analysis is time-consuming and requires complex data processing and programming skills. Therefore, a simple alternative method for evaluating the KEM is required in clinical practice.

The association between the lower limb joint angle and the KEM during landing and squatting tasks in healthy individuals has been studied. [13–18] Participants with decreased knee and hip joint flexion demonstrate a large KEM during landing. [13,14] In addition, instructions to land softly and increase the angular excursion of knee flexion reduce the KEM during landing. [15] Conversely, large knee flexion and ankle dorsiflexion angles increase the KEM during double-leg squatting in healthy individuals.[16,17] Large knee flexion and ankle dorsiflexion angles can increase the KEM because of the distance of the vector of the ground reaction force away from the knee joint. Squatting is a low-impact movement, while landing is a high-impact movement.[19] And there may be a difference in the association between the KEM and lower limb joint angle during high- and low-impact tasks. Regarding patients after ACLR, an increased KEM is associated with larger knee flexion angles during single-leg squatting.[18] Conversely, a systematic review revealed that although patients undergoing ACLR commonly exhibited asymmetry in KEM during landing, most patients did not show asymmetry in the lower limb joint angles.[10] Even after ACLR, the relationship between the KEM and lower joint angles during high-impact tasks, such as a landing task, may differ from that during squatting tasks. According to a systematic review,[10] the KEM during landing tasks may not be associated with lower limb joint angles. However, the relationship between the KEM and lower limb joint angles during landing following ACLR is unclear.

The relationships among the position of the center of pressure (COP), vertical ground reaction force (VGRF), and the KEM during squatting and landing tasks have been recently reported.[16,20–22] An expensive 3-dimensional motion analysis system is required for calculating the KEM, whereas the COP and VGRF are measured simply using force plates. Symmetry in the VGRF was associated with symmetry in the KEM during a landing task.[21] The anterior–posterior COP position significantly predicts the contribution of KEM during double-leg squatting.[16] The KEM can be modified by feedback in the anterior–posterior COP position during double-leg squatting. .[22] Additionally, symmetry in KEM is associated with symmetry in the anterior–posterior COP position and VGRF during squatting after ACLR.[20] The COP is the point location of the vector of the ground reaction force and can contribute to the lower limb joint moments by changing the length of lever arm. [23,24] If the anterior–posterior COP position moves posteriorly, the vector of the VGRF may move away from the knee joint in the sagittal plane and the KEM may increase. Few studies have investigated these relationships among the COP position, VGRF, and KEM during landing tasks. The posterior COP position is associated with a large KEM during single-leg landing in healthy individuals.[25] According to previous studies, assessing the COP position and VGRF may be useful for evaluating the KEM during landing in patients following ACLR. However, to the best of our knowledge, the relationships among the COP position, VGRF, and KEM during landing tasks in patients following ACLR have not been previously investigated.

Understanding the relationships among the anterior–posterior COP position, VGRF, lower limb joint angles, and KEM during landing following ACLR may help clinicians improve asymmetry in KEM during landing tasks. Measuring the anterior–posterior COP position, VGRF, and lower limb joint angles may be simple alternatives to evaluating the KEM. Therefore, the aim of this study was to examine the relationships among the anterior–posterior COP position, VGRF, lower limb joint angles, and KEM during landing in patients following ACLR. The hypotheses were that a large KEM would be associated with a posterior COP position and large VGRF but not with the lower limb joint angles during landing, and that the limb symmetry index (LSI) of the KEM would be associated with that of the anterior–posterior COP position and VGRF.

Methods

Participants

A priori power analysis was performed using the correlation coefficient between the KEM and anterior–posterior COP position with an effect size (r) of .62, an alpha level (α) of .05, and a statistical power ($1-\beta$) of 0.8 based on a previous study.[25] This analysis indicated that 18 participants were needed. Considering the possibility of data deficiency, 22 female athletes (mean ± standard deviation, 15.9 ± 2.0 years; height, 160.7 ± 3.6 cm; weight, 55.4 ± 6.0 kg; and preinjury modified Tegner activity score, 7.0 ± 0.7) who had undergone ACLR with semitendinosus or semitendinosus and gracilis tendon autografts participated in this study between January 2017 and April 2020. The time from surgery was 7.9 ± 1.7 months (range, 5.3–11.8 months). The preinjury sports of the participants were basketball (n = 15), gymnastics (n = 3), soccer (n = 2), handball (n = 1), and tennis (n = 1). The inclusion criteria included unilateral ACL injury, age <25 years, and preinjury modified Tegner activity scale score of ≥6. The exclusion criteria included presence of concomitant cartilage or ligament injury and a history of serious lower-extremity injuries or surgeries. Ten patients underwent concomitant meniscal repair. All participants followed a similar stepwise rehabilitation protocol wherein they started running at 3 months, jump landing at 4–5 months, and pursuing sports-specific exercises at 5–6 months after ACLR. They were allowed to return to sports 6–9 months after ACLR. The patients participated in this study when they were able to perform jump landings and start sport-specific exercises. The range of time from the surgery was large because some participants deviated from the rehabilitation protocol for delayed knee functional recovery and geographical reasons (such as greater distances between their regions of residence and our hospital). All participants gave informed consent before participating in the study. The ethics approval was obtained from the Institutional Review Boards of the Hirosaki University Graduate School of Medicine (approval number: 2016-002).

Procedures and data collection

Anthropometric measurements were recorded for each participant, including height, weight, knee and ankle widths, anterior superior iliac spine (ASIS) width, and leg length.

Retroreflective markers were placed at the pelvis and lower limbs. The drop vertical jump task was used to evaluate the KEM because the asymmetry in the KEM displayed during this task is a significant predictor of a second ACL injury.[5] The participants were asked to drop from a 35 cm-high box, land on 2 force plates (BP400600-2000, AMTI, Watertown, MA, USA) with 1 foot on each force plate, and perform a maximum jump immediately after landing. The participant performed all testing procedures with barefoot to eliminate the influences of shoes on lower limb kinematics and kinetics.[26] The participants underwent 2 to 5 practice trials to familiarize themselves with the landing task prior to data collection. Failed trials were defined as those wherein the participants did not land on the force plate and were excluded from the data analysis. Two successful trials of the drop vertical jump task were conducted.

All data were collected using a motion analysis system (Vicon Nexus; Vicon Motion Systems Ltd., Oxford, UK) equipped with 8 infrared cameras (MX-T10; Vicon Motion Systems Ltd.) and force plates. The marker coordinate data were sampled at a rate of 120 Hz, while the force plate data were sampled at 1200 Hz. Retroreflective markers were placed on the landmarks of both ASISs and the posterior superior iliac spines, lateral thighs, lateral femoral condyles, lateral shanks, lateral malleoli, heels, and second metatarsal heads according to the Plug-In Gait marker set.[27,28]

Data processing and reduction

All data were processed using the Vicon Nexus Software. Ground reaction force and marker coordinate data were filtered with a 12 Hz zero-lag, fourth-order Butterworth low-pass filter. The lower extremity joint angles were calculated using the Cardan sequence. Positive angles indicated knee flexion, hip flexion, and ankle dorsiflexion. The internal KEM was determined using inverse dynamics. The moment was normalized to the product of body mass and height, whereas the vertical reaction force was normalized to body mass. The anterior–posterior COP position was indicated as a percentage based on the distance from the second metatarsal head marker (0%) to the heel marker (100%). Thus, a large anterior–posterior COP position indicated a posterior COP position. All data were calculated during the landing phase, which was described as the initial contact (IC) and the instance of peak knee flexion during the drop vertical jump. The first landing during the drop vertical jump was analyzed. IC was defined as the first VGRF exceeding 10 N.[29] The peak KEM was computed during the landing phase. Furthermore, the hip and knee flexion and ankle dorsiflexion angles, VGRF, and anterior–posterior COP positions were computed at the peak KEM. To assess interlimb asymmetry, the LSI was calculated by dividing the value in the surgical limb by that in the non-surgical limb. The mean of the 2 trials for the landing task was used for statistical analyses.

Statistical analyses

Paired *t*-tests or Wilcoxon signed-rank tests were used to compare all values between the surgical and non-surgical limbs , depending on the normality of the values examined using Shapiro-Wilk tests. Pearson's or Spearman's correlation coefficients were used to determine the association between the peak KEM and the lower-extremity angles, VGRF, anterior–posterior COP position in the surgical and non-surgical limbs, and LSI, depending on the normality of the values. Finally, stepwise multiple regression analyses were used to determine the contribution of the variables that were significant in the correlation analyses to the KEM in the surgical and non-surgical limbs, and LSI. IBM SPSS Statistics 26 software (IBM, Armonk, NY, USA) was used for all statistical analyses. The level of significance was set at $P < .05$.

Results

The peak KEM in the surgical limb during the landing phase was significantly smaller than the peak KEM in the non-surgical limb ($P = .001$; 95% CI, 0.18 to 0.64). In addition, the participants exhibited a significantly smaller VGRF in the surgical limb than the VGRF in the non-surgical limb ($P = .005$; 95% CI, 0.88 to 4.39). However, there were no significant differences in the COP or kinematic data did not differ significantly between limbs (Table 1, Figure 1).

The KEM was significantly correlated with the anterior–posterior COP position in the surgical limb (P = .015, R = .513). No significant correlations were noted between the KEM and other measurements in the surgical limb (Table 2). However, in the non-surgical limb, the KEM was significantly correlated with the VGRF (P = .018, R = .500) but not with any other measurements in the non-surgical limb (Table 2). An analysis of the LSI revealed a significant correlation between the KEM and the VGRF (P < .001, R = .692). No significant correlation was noted between the KEM and other measurements (Table 3).

The KEM in the surgical limb was significantly predicted by the anterior-posterior COP position (P = .015, R^2 = .227, β =.513; Figure 2). The KEM was significantly predicted by the VGRF in the non-surgical limb (P = .018, R^2 = .213, β =.500; Figure 3). Multiple regression analysis of the LSI showed the KEM was significantly predicted by the VGRF (P < .001, R^2 = .621, β =.800; Figure 4).

Discussion

In this study, the KEM was significantly predicted by the anterior–posterior COP position and VGRF in the surgical and non-surgical limbs during landing, respectively. The LSI of the KEM significantly predicted the LSI of the VGRF during landing. Furthermore, the lower limb joint angles were not associated with the KEM. Therefore, these findings partially support our hypotheses.

While the anterior–posterior COP position predicted the KEM in the surgical limb, the

VGRF predicted the KEM in the non-surgical limb in this study. These findings were partially consistent with those of previous studies involving landing and squatting tasks.[16,20,21,25] This is the first study to present an association between the KEM and anterior–posterior COP position during landing after ACLR. The anterior–posterior COP position can determine the ground reaction force effect on the sagittal joint moment because the COP is the point at which the average position of the ground reaction force acts on the foot.[23,24] Posterior shift of the anterior–posterior COP position can shift the vector of the ground reaction force away from the knee joint in the sagittal plane and increase the KEM, and vice versa. The anterior–posterior COP position can contribute to the length of lever arm, which is the distance between the point of ground reaction force and the knee joint, and consequently alter the knee joint moments. Therefore, the anterior–posterior COP position may have predicted the KEM in this study. The magnitude of the VGRF is an important factor for determining knee moments when using inverse dynamics.[21] Therefore, the KEM in the non-surgical limb may have been predicted by the VGRF in the present study. The risk of secondary ACL injury of the non-surgical limb after unilateral ACLR is higher than that of an ACL injury occurring for the first time in a previously uninjured athlete.[30] Patients following ACLR demonstrate compensation that may shift loads to the non-surgical limb to reduce the VGRF and KEM in the surgical limb during double-leg tasks. In sports activities, the movement that is dependent on the non-surgical limb may be related to secondary ACL injury of the non-surgical limb.

Therefore, the VGRF, which is associated with the KEM and can be easily measured, should be evaluated during the landing task in the non-surgical limb. However, in this study, the measurements associated with the KEM differed between the limbs. The present study revealed that the KEM and VGRF in the surgical limb was smaller than those in the non-surgical limb. The participants may have decreased the VRGF in the surgical limb by dividing the larger loads to the non-surgical limb, and then shifted anterior–posterior COP forward as strategies to further reduce the KEM in the surgical limb.

In the present study, the LSI of the VGRF predicted the LSI of the KEM with a significant correlation. These findings supported the results of previous studies that analyzed stop-jump and double-leg squatting tasks.[20,21,31] The VGRF is an important factor for calculating knee kinetics when using inverse dynamics.[21] Therefore, the LSI of the KEM may have been associated with the VGRF in this study. Asymmetry in the KEM during the landing task is a predictor of secondary ACL injuries in athletes after ACLR.[5] The LSI of KEM during the landing task should be evaluated to prevent secondary ACL injuries. Evaluating the KEM is challenging in the clinical setting because a 3-dimensional motion analysis system is required, whereas the VGRF can be estimated relatively easily using force plates. Therefore, evaluating the LSI of the VGRF may be helpful for clinicians to understand the LSI of the KEM for the prevention of secondary ACL injuries.

There were no significant associations between the KEM and lower limb joint angles in the present study. These results are inconsistent with the findings of previous studies that used squatting tasks.[16–18] A systematic review revealed that asymmetries between surgical and non-surgical limbs were found to be more common in the kinetic variables than in the kinematic variables during landing tasks.[10] In the present study, while the KEM and VGRF in the surgical limb were smaller than those in the non-surgical limb, the lower limb joint angles did not differ between the 2 limbs, thereby supporting the findings of the aforementioned systematic review. In addition, there were significant associations between the KEM and the anterior–posterior COP position and VGRF. The KEM and VGRF are higher during landing tasks than during squatting tasks.[19] Unlike during low-impact and slow movements (such as squatting and lunges), the KEM may not be controlled by the lower-limb joint angle but by the anterior–posterior COP position and VGRF during high-impact and ballistic movements (such as landing, jumping, and cutting). Patients after ACLR demonstrate increased trunk flexion in the surgical limb compared with the non-surgical limb or with healthy individuals during a single-leg landing task because of compensation for decreased KEM.[32,33] A small KEM is associated with the trunk flexion motion, which may displace the vector of the ground reaction force anteriorly toward the knee joint.[16,34] In addition, trunk flexion better predicts the KEM than shank inclination. [34] The compensatory pattern of increased trunk flexion may attenuate the association between the KEM and the lower limb joint angles. However, trunk kinematics were not investigated in this study. Future studies should examine the association between the KEM and trunk kinematics.

The anterior–posterior COP position explained 23% of the variance in the KEM in the surgical limb, whereas the VGRF explained 21% of the variance in the KEM in the non-surgical limb. The remaining 77% and 79%, respectively, were not explained by the anterior–posterior COP position, VGRF, and lower limb joint angles. Meanwhile, 62% of the variance in the LSI of the KEM was explained by that of the VGRF. The value of the explained variance was higher than that in the surgical and non-surgical limbs. The LSI of the KEM can be predicted by trunk kinematics during landing tasks.[35] Better prediction may require trunk kinematics.

This study had some limitations. First, it only included female patients who underwent ACLR. There are sex-based differences in landing biomechanics.[36] Therefore, the relationship between the KEM and VGRF, anterior–posterior COP position, and lower limb joint angles in male patients following ACLR should be investigated in future studies. Second, the range of the time from the participants' surgery was large (range: 5.3–11.8 months). Symmetry in the landing biomechanics improves with time in patients after ACLR.[37,38] Further studies should be conducted at the same time points after surgery. Third, the KEM is associated with trunk flexion and lateral flexion angle during squatting.[16,18,34] However, only lower limb markers from the Plug-In Gait marker set were placed in this study. In addition, the landing position of the foot segment (i.e. whether the patients landed on the forefoot, midfoot, or rearfoot) can affect the KEM because of the shift in the COP position.[39] The associations among the KEM, trunk kinematics, and landing position of the foot segment during landing were not investigated in this study and should be examined. Fourth, only the landing phase was analyzed because asymmetry in KEM during landing is considered a risk factor for secondary ACL injuries.[5] However, some participants may exhibit peak KEM after peak knee flexion. Future studies should analyze the phase between the contact and toe off the force. Fifth, this study used multiple statistical tests without alpha adjustment. Similar statistical comparisons of kinetics and kinematics were used in previous studies with similar study designs.[40-42] However, it should be recognized that repeated testing may increase the study-wise type I error rate. Finally, this study only examined double-leg landings. The association between the KEM and the VGRF and anterior–posterior COP positions during single-leg landing may differ from the outcomes of this study.

Following ACLR, most patients have a smaller KEM in the surgical limb than in the non-surgical limb and asymmetry in KEM during landing.[10] Asymmetry in KEM during landing is a risk factor for secondary ACL injuries.[5] Therefore, it is important to evaluate the KEM during landing for the prevention of secondary ACL injuries. However, evaluating the KEM during landing tasks is challenging in the clinical setting because an expensive 3-dimensional motion analysis system is required for data collection and analysis. Furthermore, 3-dimensional motion analysis is time-consuming and requires complex data processing and programming skills. Conversely, the anterior–posterior COP position and VGRF can be evaluated relatively easily using a force plate. The results of this study showed that the VGRF and anterior–posterior COP position explained 21–62% of the variance in the KEM, and support the use of the VGRF and anterior–posterior COP positions as an alternative to the KEM for assessing landing biomechanics in the clinical setting.

Conclusion

This study revealed that the LSI of the KEM was significantly predicted by the LSI of the VGRF. The KEM was significantly predicted by the anterior–posterior COP position in the surgical limb and the VGRF in the non-surgical limb. No significant correlations between the KEM and the lower limb joint angles were identified. These findings indicate that evaluating the VGRF and anterior–posterior COP position, not the lower limb joint angles, may contribute to understanding the KEM during double-leg landing after ACLR in the clinical setting.

Acknowledgments

We would like to thank Editage (https://www.editage.jp/) for English language editing.

Funding

None declared.

Conflict of interest

None declared.

References

1. Ishibashi Y, Adachi N, Koga H, et al. Japanese Orthopaedic Association (JOA) clinical practice guidelines on the management of anterior cruciate ligament injury – secondary publication. *J Orthop Sci*. 2020;25(1):6–45. doi:10.1016/j.jos.2019.10.009
2. Keizer MNJ, Otten E. Passive anterior tibia translation in anterior cruciate ligament-injured, anterior cruciate ligament-reconstructed and healthy knees: a systematic review. *Musculoskelet Surg*. 2019;103(2):121–130. doi:10.1007/s12306-018-0572-6
3. Spindler KP, Huston LJ, Chagin KM, et al. Ten-year outcomes and risk factors after anterior cruciate ligament reconstruction: a MOON longitudinal prospective cohort study. *Am J Sports Med*. 2018;46(4):815–825. doi:10.1177/0363546517749850
4. Wiggins AJ, Grandhi RK, Schneider DK, et al. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med*. 2016;44(7):1861–1876. doi:10.1177/0363546515621554
5. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968–1978. doi:10.1177/0363546510376053
6. King E, Richter C, Daniels KAJ, et al. Biomechanical but not strength or performance measures differentiate male athletes who experience ACL reinjury on return to level 1

sports. *Am J Sports Med.* 2021;49(4):918–927. doi:10.1177/0363546520988018

7. King E, Richter C, Daniels KAJ, et al. Can biomechanical testing after anterior cruciate ligament reconstruction identify athletes at risk for subsequent ACL injury to the contralateral uninjured limb? *Am J Sports Med*. 2021;49(3):609–619. doi:10.1177/0363546520985283

8. Cronström A, Tengman E, Häger CK. Risk factors for contra-lateral secondary anterior cruciate ligament injury: a systematic review with meta-analysis. *Sports Med*. 2021;51(7):1419–1438. doi:10.1007/s40279-020-01424-3

9. Johnston PT, McClelland JA, Webster KE. Lower limb biomechanics during single-leg landings following anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Sports Med*. 2018;48(9):2103–2126. doi:10.1007/s40279-018-0942-0

10. Hughes G, Musco P, Caine S, Howe L. Lower limb asymmetry after anterior cruciate ligament reconstruction in adolescent athletes: a systematic review and meta-analysis. *J Athl Train*. 2020;55(8):811–825. doi:10.4085/1062-6050-0244-19

11. Webster KE, Ristanis S, Feller JA. A longitudinal investigation of landing biomechanics following anterior cruciate ligament reconstruction. *Phys Ther Sport*. 2021;50:36–41. doi:10.1016/j.ptsp.2021.03.012

12. Peebles AT, Miller TK, Savla J, et al. Reduction of risk factors for ACL Re-injuries

using an innovative biofeedback approach: a phase I randomized clinical trial. *Phys Ther Sport*. 2022;57:78–88. doi:10.1016/j.ptsp.2022.07.007

13. Malfait B, Dingenen B, Smeets A, et al. Knee and hip joint kinematics predict quadriceps and hamstrings neuromuscular activation patterns in drop jump landings. *PLoS One*. 2016;11(4):1–18. doi:10.1371/journal.pone.0153737

14. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clin Biomech*. 2010;25(2):142–146. doi:10.1016/j.clinbiomech.2009.10.005

15. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sport Phys Ther*. 2008;38(6):353–361. doi:10.2519/jospt.2008.2726

16. Ishida T, Samukawa M, Kasahara S, Tohyama H. The center of pressure position in combination with ankle dorsiflexion and trunk flexion is useful in predicting the contribution of the knee extensor moment during double-leg squatting. *BMC Sports Sci Med Rehabil*. 2022;14(1):127. doi:10.1186/s13102-022-00523-0

17. Lorenzetti S, GüLay T, Stoop M, et al. Comparison of the angles and corresponding moments in the knee and hip during restricted and unrestricted squats. *J Strength Cond Res*. 2012;26(10):2829–2836. doi:10.1519/JSC.0b013e318267918b

18. Bell DR, Kulow SM, Stiffler MR, Smith MD. Squatting mechanics in people with and

without anterior cruciate ligament reconstruction: the influence of graft type. *Am J Sports Med*. 2014;42(12):2979–2987. doi:10.1177/0363546514552630

19. Song Y, Li L, Jensen MA, Dai B. Jump-landing kinetic asymmetries persisted despite symmetric squat kinetics in collegiate athletes following anterior cruciate ligament reconstruction. *Sport Biomech*. 2023;00(00):1-14. doi:10.1080/14763141.2023.2207552

20. Chan MS, Sigward SM. Center of pressure predicts Intra-limb compensatory patterns that shift demands away from knee extensors during squatting. *J Biomech*. 2020;111:110008. doi:10.1016/j.jbiomech.2020.110008

21. Dai B, Butler RJ, Garrett WE, Queen RM. Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction. *Scand J Med Sci Sports*. 2014;24(6):974–981. doi:10.1111/sms.12118

22. Ishida T, Samukawa M, Endo D, Kasahara S, Tohyama H. Effects of changing center of pressure position on knee and ankle extensor moments during double-leg squatting. *J Sports Sci Med*. 2022;21(3):341–346. doi:10.52082/jssm.2022.341

23. Winter DA. Human balance and posture control during standing and walking. *Gait Posture*. 1995;3(4):193–214. doi:10.1016/0966-6362(96)82849-9

24. Gruben KG, Boehm WL. Mechanical interaction of center of pressure and force direction in the upright human. *J Biomech*. 2012;45(9):1661–1665.

doi:10.1016/j.jbiomech.2012.03.018

25. Shimokochi Y, Yong Lee S, Shultz SJ, Schmitz RJ. The relationships among sagittal-plane lower extremity moments: implications for landing strategy in anterior cruciate ligament injury prevention. *J Athl Train*. 2009;44(1):33–38. doi:10.4085/1062-6050-44.1.33

26. Hong YG, Yoon YJ, Kim P, Shin CS. The kinematic/kinetic differences of the knee and ankle joint during single-leg landing between shod and barefoot condition. *Int J Precis Eng Manuf*. 2014;15(10):2193–2197. doi:10.1007/s12541-014-0581-9

27. Davis RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. *Hum Mov Sci*. 1991;10(5):575–587. doi:10.1016/0167-9457(91)90046-Z

28. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res*. 1990;8(3):383–392. doi:10.1007/978-1-4471-5451-8_100

29. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: Implications for longitudinal analyses. *Med Sci Sports Exerc*. 2007;39(11):2021–2028. doi:10.1249/mss.0b013e318149332d

30. Swärd P, Kostogiannis I, Roos H. Risk factors for a contralateral anterior cruciate ligament injury. *Knee Surgery, Sport Traumatol Arthrosc*. 2010;18(3):277–291.

doi:10.1007/s00167-009-1026-3

31. Ishida T, Samukawa M, Koshino Y, et al. Pelvic rotation is associated with asymmetry in the knee extensor moment during double-leg squatting after anterior cruciate ligament reconstruction. *J Appl Biomech*. 2023;39(1):62–68. doi:10.1123/jab.2022-0204

32. Ithurburn MP, Paterno M V., Ford KR, Hewett TE, Schmitt LC. Young athletes with quadriceps femoris strength asymmetry at return to sport after anterior cruciate ligament reconstruction demonstrate asymmetric single-leg drop-landing mechanics. *Am J Sports Med*. 2015;43(11):2727–2737. doi:10.1177/0363546515602016

33. Oberländer KD, Brüggemann GP, Höher J, Karamanidis K. Altered landing mechanics in ACL-reconstructed patients. *Med Sci Sports Exerc*. 2013;45(3):506 –513. doi:10.1249/MSS.0b013e3182752ae3

34. Straub RK, Barrack AJ, Cannon J, Powers CM. Trunk inclination during squatting is a better predictor of the knee-extensor moment than shank inclination. *J Sport Rehabil*. 2021;30(6):899–904. doi:10.1123/JSR.2020-0397

35. Song Y, Li L, Jensen MA, Dai B. Using trunk kinematics to predict kinetic asymmetries during double-leg jump-landings in collegiate athletes following anterior cruciate ligament reconstruction. *Gait Posture*. 2023;102:80–85. doi:10.1016/j.gaitpost.2023.03.003

36. Sullivan ZB, Sugarman BS, Faherty MS, et al. Females have lower knee strength and vertical ground reaction forces during landing than males following anterior cruciate ligament reconstruction at the time of return to sport. *Int J Sports Phys Ther*. 2022;17(4):556–565. doi:10.26603/001c.35575

37. Ishida T, Samukawa M, Suzuki M, et al. Improvements in asymmetry in knee flexion motion during landing are associated with the postoperative period and quadriceps strength after anterior cruciate ligament reconstruction. *Res Sports Med*. 2023;31(3):285–295. doi:10.1080/15438627.2021.1966010

38. Renner KE, Franck CT, Miller TK, Queen RM. Limb asymmetry during recovery from anterior cruciate ligament reconstruction. *J Orthop Res*. 2018;36(7):1887–1893. doi:10.1002/jor.23853

39. Ogasawara I, Shimokochi Y, Mae T, Nakata K. Rearfoot strikes more frequently apply combined knee valgus and tibial internal rotation moments than forefoot strikes in females during the early phase of cutting maneuvers. *Gait Posture*. 2020;76:364–371. doi:10.1016/j.gaitpost.2019.11.014

40. Edwards S, Steele JR, Cook JL, Purdam CR, McGhee DE. Lower limb movement symmetry cannot be assumed when investigating the stop-jump landing. *Med Sci Sport Exerc*. 2012;44(6):1123–1130. doi:10.1249/MSS.0b013e31824299c3

41. Wild CY, Grealish A, Hopper D. Lower limb and trunk biomechanics after fatigue in

competitive female Irish dancers. *J Athl Train*. 2017;52(7):643–648. doi:10.4085/1062-6050-52.3.12

42. Chijimatsu M, Ishida T, Yamanaka M, et al. Subsequent jumping increases the knee and hip abduction moment, trunk lateral tilt, and trunk rotation motion during single-leg landing in female individuals. *J Appl Biomech*. 2023;39(4):223–229. doi:10.1123/jab.2022-0305

Table 1. Comparison of the knee extensor moment, vertical ground reaction force, anterior–posterior COP position, and knee, hip, and ankle kinematics between the surgical and non-surgical limbs.

	Surgical limb	Non-surgical limb	*P* value
Peak knee extensor moment [Nm/kg/m]	1.43 (0.33)	1.84 (0.41)	**.001**
Vertical ground reaction force [N/kg]	11.9 (2.3)	14.6 (3.5)	**.005**
Anterior–posterior COP position [%]	13.3 (9.1)	14.8 (9.8)	.486
Knee flexion angle[a] [degree]	76.2 (10.4)	78.2 (12.8)	.408
Hip flexion angle[a] [degree]	57.7 (7.4)	57.6 (10.1)	.615
Ankle dorsiflexion angle [degree]	25.7 (4.0)	27.1 (5.0)	.173

Anterior–posterior COP: anterior-posterior center of pressure

Data are presented as mean (SD).

Bold font indicates a significant difference ($P < .05$).

The large value of the anterior–posterior COP position indicates a posterior COP position.

All values are identified at the time of the peak knee extensor moment.

[a] Nonparametric data.

Table 2. Correlation coefficients between the knee extensor moment and the vertical ground reaction force, anterior–posterior COP position, and knee, hip, and ankle kinematics in the surgical and non-surgical limbs.

	Correlation coefficient (*r*)	*P* value
Surgical limb		
Vertical ground reaction force	.300	.175
Anterior–posterior COP position	**.513**	**.015**
Knee flexion angle	.224	.317
Hip flexion angle	.023	.919
Ankle dorsiflexion angle	.142	.528
Non-surgical limb		
Vertical ground reaction force	**.500**	**.018**
Anterior–posterior COP position	.204	.363
Knee flexion angle[a]	-.339	.122
Hip flexion angle[a]	-.382	.079
Ankle dorsiflexion angle	.025	.911

Anterior–posterior COP: anterior-posterior center of pressure

Bold font indicates a significant difference ($P < .05$).

All values are identified at the time of the peak knee extensor moment.

[a] Nonparametric data.

Table 3. Correlation coefficients between the LSI of the knee extensor moment and the LSIs of the vertical ground reaction force, anterior–posterior COP position, and knee, hip, and ankle kinematics.

	Correlation coefficient (*r*)	*P* value
Vertical ground reaction force	**.692**	**< .001**
Anterior–posterior COP position	.414	.056
Knee flexion angle	-.203	.366
Hip flexion angle	-.376	.085
Ankle dorsiflexion angle	-.108	.633

Anterior–posterior COP: anterior-posterior center of pressure

LSI: limb symmetry index

Bold font indicates a significant difference ($P < .05$).

All values are identified at the time of the peak knee extensor moment.

The LSI is calculated as the percentage value of the surgical limb relative to that of the non-surgical limb.

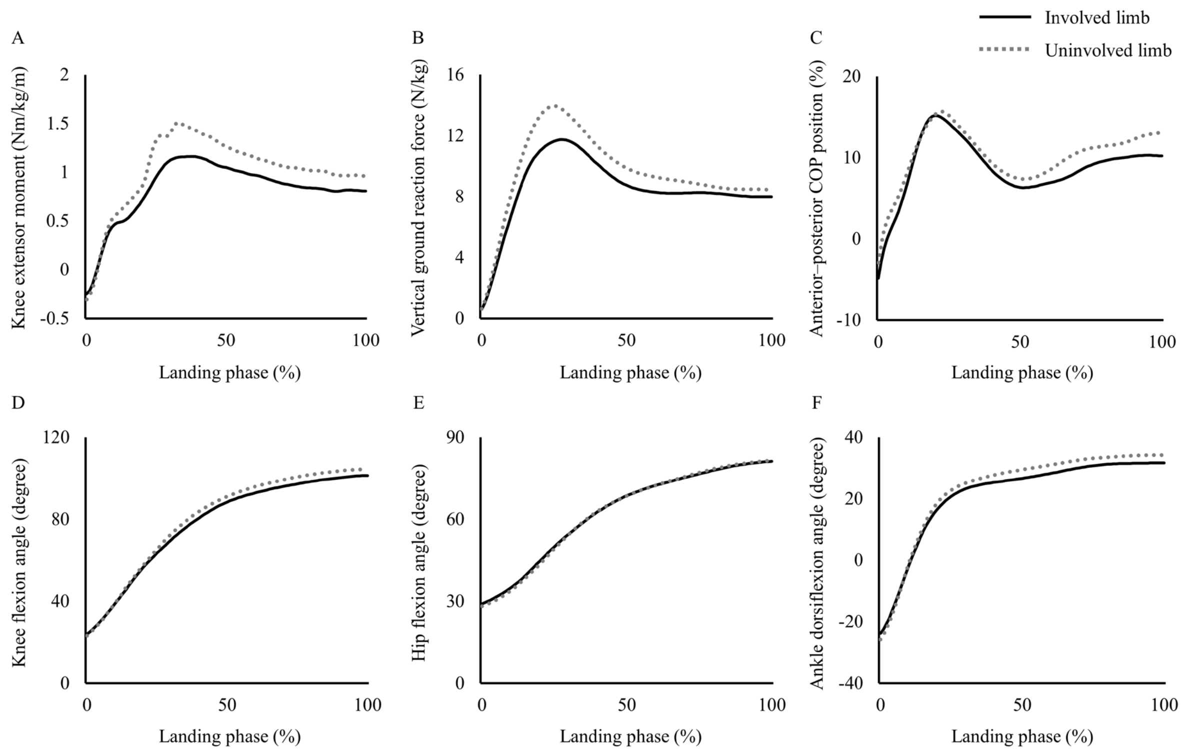

Figure 1. Average waveforms of the knee extensor moment, the vertical ground reaction force, anterior–posterior COP position, and knee, hip, and ankle kinematics in the surgical and non-surgical limb. The landing phase is described as the time between the initial contact and the maximum knee flexion during a drop vertical jump task. The large value of the anterior–posterior COP position indicates a posterior COP position. Anterior–posterior COP: anterior-posterior center of pressure. A, knee extensor moment. B, vertical ground reaction force. C, anterior–posterior COP position. D, knee flexion angle. E, hip flexion angle. F, ankle dorsiflexion angle.

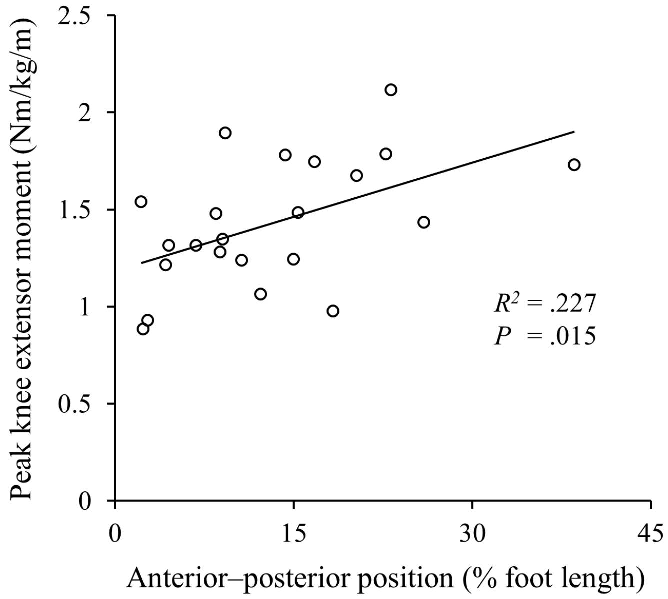

Figure 2. Scatter plot of the association between the knee extensor moment and the anterior–posterior COP position in the surgical limb. The large value of the anterior–posterior COP position indicates a posterior COP position. Anterior–posterior COP: anterior-posterior center of pressure.

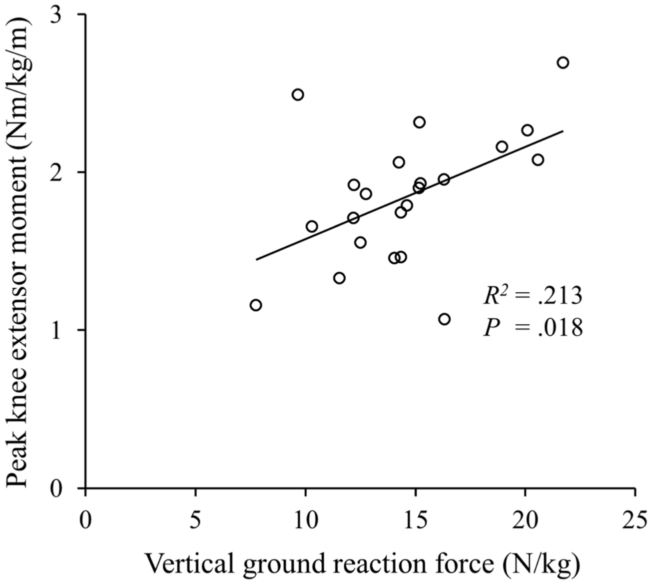

Figure 3. Scatter plot of the association between the knee extensor moment and the vertical ground reaction force in the non-surgical limb.

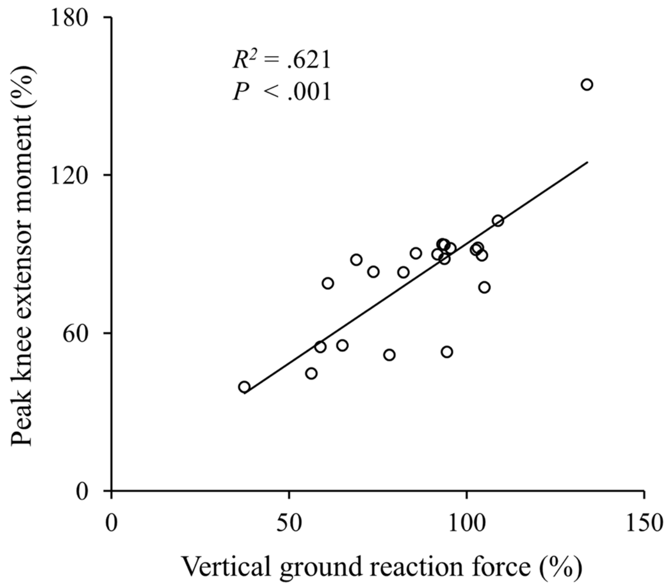

Figure 4. Scatter plot of the association between the LSI of the knee extensor moment and the LSI of the vertical ground reaction force. LSI is calculated as the percentage of the value of the surgical limb to that of the non-surgical limb. LSI: limb symmetry index.