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Pelvic rotation is associated with asymmetry in the knee extensor moment during double-leg squatting after anterior cruciate ligament reconstruction

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Abstract

Asymmetry in knee extensor moment during double-leg squatting was observed after anterior cruciate ligament reconstruction (ACLR), even after the completion of the rehabilitation program for return to sports. The purpose of this study was to clarify the association between asymmetry in the knee extensor moment and pelvic rotation angle during double-leg squatting after ACLR. Twenty-four participants performed double-leg squatting. Kinetics and kinematics during squatting were analyzed using a three-dimensional motion analysis system with two force plates. The limb symmetry index (LSI) of knee extensor moment was predicted by the pelvic rotation angle (R^2 = .376, p = .001). Additionally, the pelvic rotation and the LSI of the vertical ground reaction force (VGRF) independently explained the LSI of the knee extensor moment (R^2 = .635, p < .001, β of pelvic rotation = −0.489, β of VGRF = 0.524,). Pelvic rotation toward the involved limb was associated with a smaller knee extensor moment in the involved limb than in the uninvolved limb. The assessment of pelvic rotation would be useful for partially predicting asymmetry in the knee extensor moment during double-leg squatting. Minimizing pelvic rotation may improve the asymmetry in the knee extensor moment during double-leg squatting after ACLR.

Keywords: compensation, knee extension moment, quadriceps, motor control, rehabilitation

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Introduction

Double-leg squatting is commonly used as a basic exercise to improve lower-limb joint control after anterior cruciate ligament reconstruction (ACLR),[1-8] whereas the knee extensor moment in the involved limb is 12–38% smaller than that in the uninvolved limb during double-leg squatting after ACLR.[2-4,7,9] The persistence of asymmetry in the knee extensor moment may limit the effectiveness of exercise.[3,6-8] Quadriceps weakness in the involved limb can be observed for more than 2 years and up to 5 years after surgery.[10] Moreover, asymmetry in the knee extensor moment during double-leg squatting is positively and moderately correlated with that during the landing task after ACLR.[9] An improvement in the asymmetry in the knee extensor moment during double-leg squatting may translate to improved symmetry in the knee extensor moment during double-leg landing.[9] A second ACL injury occurs in 15% of patients,[11] while asymmetry in knee extensor moment during double-leg landing is a risk factor of second injury.[12] Additionally, although comprehensive mechanism has not been elucidated, the decreased knee loading during weight bearing activities, including double-leg squatting, has also been speculated to be a possible contributor to the early development of knee osteoarthritis after ACLR.[13-15] Therefore, an improvement in asymmetry of the knee extensor moment during weight bearing activities, including double-leg squatting, is targeted throughout the rehabilitation process for return to sports.[8,16,17] However, asymmetry in the knee extensor moment during double-leg squatting may be present for more than one year, even after completion of the rehabilitation program for return to sports.[3,7] No method has been established to improve the asymmetry of the knee extensor moment in double-leg squatting or other weight-bearing activities.[8]

The asymmetrical knee extensor moment during double-leg squatting after ACLR is associated not only with asymmetrical vertical ground reaction force (VGRF) but also with the smaller contribution of the knee extensor moment relative to hip, ankle, and support moments in the involved limb.[4,7] The ratio of the contribution of the knee extensor moment to the hip, ankle or support moment is significantly smaller in the involved limb than in the uninvolved limb.[2,4,7] Asymmetry in the knee extensor moment after ACLR was observed even in individuals demonstrating a symmetrical VGRF or support moment during double-leg squatting.[6,7] Asymmetry in the contribution of knee extensor moment is related to asymmetry in the knee extensor moment in the long term compared to the asymmetry in VGRF.[4] An improvement in asymmetry in the contribution of the knee extensor moment is needed to restore a symmetrical knee extensor moment during double-leg squatting after ACLR.

Asymmetry in the anterior-posterior (AP) center-of-pressure (COP) position is associated with asymmetry in hip-to-knee and ankle-to-knee extensor moment ratios during double-leg squatting after ACLR.[2] Asymmetry in the AP-COP position is also associated with asymmetry in the knee-to-support moment ratio of healthy individuals during double-leg squatting.[18] These findings suggest that the AP-COP position is associated with distribution among hip, knee, and ankle extensor moments during double-leg squatting. Changes in the AP-COP position are proposed to affect lower-limb joint moments in the sagittal plane by altering the distance between the VGRF vectors and the lower-limb joint centers.[2,18] On the other hand, changes in each lower limb joint position in the AP direction would also affect lower-limb joint moments in the sagittal plane by altering the distance between the VGRF and the lower limb joint centers, similar to the changes in the AP-COP position. However, asymmetry in the lower limb kinematics is not associated with asymmetry in the knee extensor moment during double-leg squatting.[18] Pelvic rotation in the horizontal plane may result in anterior or posterior shifts of the knee and hip joint centers during the double-leg squatting with both feet fixed to the ground

(Figure 1). For example, as a result of pelvic rotation toward the left side, the left knee joint might move closer to the VGRF vector while the right knee joint center might move away from the VGRF, decreasing the left knee extensor moment while increasing the right knee extensor moment (Figure 1). Therefore, pelvic rotation in the horizontal plane may be associated with asymmetry in the knee extensor moment during double-leg squatting through the redistribution among hip, knee, and ankle extensor moments, and may be a predictor of asymmetrical knee extensor moment.

The purpose of the present study was to investigate the associations of asymmetry in the knee extensor moment and knee-to-support moment ratio with the pelvic rotation angle and the AP-COP position during double-leg squatting in individuals who underwent ACLR. The hypothesis was that the pelvic rotation toward the involved side would be associated with a smaller knee extensor moment and knee-to-support moment ratio in the involved limb than in the uninvolved limb. The combination of pelvic rotation, asymmetry in the AP-COP position and asymmetry in VGRF would provide a better prediction of asymmetry in the knee extensor moment.

Methods

Participants: The present study enrolled 24 participants (Table 1). A prior sample size calculation showed that 21 participants were needed to achieve an alpha level (α), statistical power ($1 - \beta$) and a regression coefficient of 0.05, 0.8, and 0.3 respectively. The assumption of a correlation coefficient was based on a previous study showing the relationship between the interlimb asymmetries in the AP-COP position and knee extensor moment.[2] The inclusion criteria were as follows: (1) primary unilateral ACLR, (2) no restriction for sport activities, and (3) no pain during double-leg squatting. Participants were excluded if they had undergone bilateral or revision ACLR or had a history of knee injuries in the involved or uninvolved limb except for primary ACLR. Written informed consent was obtained from each participant before participation. This study was approved by the Institutional Review Board of the Faculty of Health Sciences, Hokkaido University (approval number: 19-72).

Procedures: A five-minute warm-up was performed with a stationary bicycle ergometer at a self-selected pace. After the warm-up, a total of 26 retroreflective markers were placed on the iliac crest, anterior and posterior superior iliac spines (ASISs and PSISs, respectively), lateral thigh, medial and lateral femoral epicondyle, lateral shank, medial and lateral malleoli, second metatarsal head and base, fifth metatarsal head and heel. First, a standardized static standing trial was recorded. Then, participants performed three trials of five consecutive double-leg squats. They stood with their feet shoulder-width apart, with one foot on an individual force plate and arms crossed over their chest. They were asked to squat down such that their thighs were parallel to the floor and then return to the upright standing position.[3] If their heels were off the floor, they were asked to squat as deeply as possible without their heels coming off the floor. A metronome was used to help participants squat for 2 seconds each for descent and ascent.[3] The participants were allowed to rest between each trial as needed. The rest time was usually two to three minutes.

All data were recorded using a motion capture system (Cortex version 5.0.1, Motion Analysis Corp., Santa Rosa, CA, USA) with seven high-speed digital cameras (Hawk cameras, Motion Analysis Corp.) and two synchronized force plates (Type 9286, Kistler AG, Winterthur, Switzerland). The sampling rates were set to 200 Hz for the marker coordinate data and 1,000 Hz for the force plate data.

Knee extensor strength was tested after biomechanical experiments to characterize the participants. Isokinetic concentric torque at $60°\cdot s^{-1}$ was assessed with a dynamometer (Biodex System 3, Biodex Medical Systems, Inc., Shirley, NY) using a previously described method.[19] The limb symmetry index (LSI) was calculated as the percentage of the peak torque in the involved side to that in the uninvolved side. Nine of the participants were considered to have strength deficits (LSI < 90%)[20] (Table 1).

Data analysis: Data processing and reduction were performed using Visual3D (version 6, C-Motion, Inc., Germantown, MD, USA) and MATLAB 2021b (MathWorks, Inc., Natick, MA, USA). Marker trajectories and force plate data were low-pass filtered using a fourth-order, zero-lag Butterworth filter with a 12-Hz cutoff frequency.[2,4] When the ASIS markers were missing during the squatting task, iliac crest and PSIS markers were used to fill ASIS marker trajectory gaps.[21] The hip joint center was estimated based on a previous study,[22] while the knee and ankle joint centers were calculated as the midpoint between the medial and lateral epicondyles, and between the medial and lateral malleoli, respectively. Hip, knee, and ankle joint angles and moments were calculated using a joint coordinate system with the Cardan X-Y-Z sequence. In calculating joint moments, the segment inertial parameters were set as described in a previous report.[23] Moreover, the knee-to-support moment ratio was calculated, and the support moment was calculated as the sum of the hip, knee, and ankle extensor moments.[7] The pelvic rotation angle was calculated as the angle between the bilateral hip joint line and ankle joint line on the horizontal plane (Figure 2). A positive angle indicates rotation toward the involved side. In addition, the AP-COP position of each foot was calculated. The AP-COP direction was adjusted by the vector from the heel marker to the 2nd metatarsal head marker.[2] The AP-COP position was calculated as the percentage of the foot length (% foot length), which was defined as the distance from the heel marker (0%) to the second metatarsal head marker (100%).[2]

The analysis was conducted at the peak knee flexion angle during squatting because the knee extensor moment and asymmetry in the knee extensor moment were the largest at this time in patients after ACLR.[24,25] In addition, the mean values were calculated for the phase in which the knee was flexed more than 60° to evaluated tendency across the squatting task because this phase is of clinical interest.[26] Interlimb asymmetry was assessed by calculating the LSI, which was calculated as the percentage of the involved limb to the uninvolved limb.[2,4,18] All variables were averaged across the middle three of the five consecutive squats of the three trials.[4,18]

The test-retest reliability of the pelvic rotation angle was assessed by calculating intraclass correlation coefficients (ICCs) and typical errors.[27] The retest was conducted for 14 participants with a one-week interval. The ICCs (1, k) were .892 for the pelvis angle at peak knee flexion and .896 for the mean pelvis angle. Typical errors were 0.64° for the pelvis angle at peak knee flexion and 0.57° for the mean pelvis angle.

Statistical analysis: Data are presented as the means and standard deviations (SD). In addition, the number of participants showing an LSI of knee extensor moment less than 90% was reported.[28] A statistical analysis was performed for each of the values at peak knee flexion and the mean values. A univariate regression analysis was performed to examine the linear relationship between the LSI of the knee extensor moment and knee-to-support moment ratio, and the pelvic rotation angle and the LSI of the AP-COP position. Moreover, a stepwise regression analysis was conducted to determine the independent predictive ability of the pelvic rotation angle, the LSI of the AP-COP position and the VGRF for the LSI of the knee extensor moment and knee-to-support moment ratio. The final regression model was determined based on the minimum Akaike information criterion. Additionally, the linear relationships between the pelvic rotation angle and the LSI of the VGRF, and the AP-COP position were confirmed using a linear regression analysis. The statistical significance level was set to $p < .05$. These statistical analyses were performed using JMP Pro software (version 15, SAS Institute Inc., Cary, NC, USA).

Results

The LSI of the knee extensor moment at peak knee flexion was 100.8 ± 19.9%, and nine participants (38%) showed an LSI less than 90%. Meanwhile, the LSI of the mean knee extensor moment during knee flexion at angles larger than 60° was 100.2 ± 19.1%, and eight participants (33%) showed an LSI less than 90%. The pelvic rotation angle was −0.1 ± 2.4° (maximum: 4.8°, minimum: −6.4°) at peak knee flexion and −0.1 ± 2.2° (maximum: 5.1°, minimum: −5.2°) for the mean value. The SDs of pelvic rotation angles among trials within each participant were 1.3 ± 0.5° at peak knee flexion and 1.1 ± 0.5° for the mean value. The LSI of the knee extensor moment was predicted by the pelvic rotation angle at peak knee flexion ($R^2 = .376$, $p = .001$) (Figure 3a) but not by the LSI of the AP-COP position (Figure 3b). Pelvic rotation toward the involved limb was associated with a smaller knee extensor moment in the involved limb relative to the uninvolved limb. The stepwise multivariate regression analysis showed that the LSI of the VGRF and the pelvic rotation angle explained 63% of the variance in the LSI of the knee extensor moment (model $R^2 = .635$, $p < .001$) (Table 2). The LSI of the AP-COP position was not included in the multivariate model. The LSI of the mean knee extensor moment was also predicted by the mean pelvic rotation angle ($R^2 = .242$, $B = −4.3$, intercept = 99.6, $P = .015$). The stepwise regression analysis showed that the LSIs of the mean VGRF and the mean pelvic rotation angle were significant predictors of the LSI of the mean knee extensor moment (model $R^2 = .609$, $p < .001$) (Table 2).

The LSI of the knee-to-support moment ratio was 100.5 ± 17.6% at peak knee flexion and 98.6 ± 14.6% at the mean value. The pelvic rotation angle predicted the LSI of the knee-to-support moment ratio at peak knee flexion ($R^2 = .403$, $p < .001$) (Figure 4a). Pelvic rotation toward the involved limb was associated with a smaller knee-to-support moment ratio in the involved limb relative to the uninvolved limb. The LSI of the AP-COP position also predicted the LSI of the knee-to-support moment ratio at peak knee flexion (R^2 = .398, p = .001) (Figure 4b). In the multivariate regression analysis, the LSI of the knee-to-support moment ratio was predicted by the pelvic rotation angle and the LSI of the AP-COP position (model R^2 = .596, p < .001) (Table 3). The LSI of the mean knee-to-support moment ratio was also predicted by the mean pelvic rotation angle (R^2 = .293, B = −3.7, intercept = 98.1, p = .006) and the LSI of the mean AP-COP position (R^2 = .293, B = −0.6, intercept = 161.6, p = .006). The stepwise regression analysis showed that the mean pelvic rotation angle and LSIs of the AP-COP position were significant predictors of the LSI of the mean knee-to-support moment ratio (model R^2 = .421, p = .003) (Table 3).

There was no significant linear relationship between the pelvic rotation angle and LSI of VGRF (R^2 = .056, p = .265) or the LSI of AP-COP position (R^2 = .119, p = .099) at peak knee flexion, or between the mean pelvic rotation angle and LSI of the mean VGRF (R^2 = .044, p = .325) or the LSI of the mean AP-COP position (R^2 = .155, p = .057).

Discussion

The present study revealed that the pelvic rotation angle predicted the asymmetry in the knee extensor moment and knee-to-support moment ratio during double-leg squatting in individuals who underwent ACLR. To our knowledge, this study is the first to report the association between the pelvic rotation angle and the asymmetry in the knee extensor moment and its contribution during double-leg squatting after ACLR. Furthermore, the combination of the pelvic rotation angle and the LSI of VGRF explained 63% of the variance in the LSI of knee extensor moment at the peak knee flexion and 61% of the variance at the mean value, and the combination of pelvic rotation and the LSI of the AP-COP position explained 60% of the variance in the LSI of the knee-to-support moment ratio at the peak knee flexion and 42% of the variance at the mean value. These results supported the a priori hypothesis.

During double-leg squatting, both feet are fixed to the ground. Therefore, the pelvic rotation toward the involved limb would lead to a posterior shift of the hip and knee joints on the involved side (Figure 1). Consistent with our hypothesis, pelvic rotation toward the involved limb was associated with a smaller knee extensor moment in the involved limb than in the uninvolved limb. This relationship between the pelvic rotation angle and LSI of the knee extensor moment would result from the redistribution among hip, knee, and ankle extensor moments induced by the pelvic rotation because the pelvic rotation angle was also associated with interlimb asymmetry in the knee-to-support moment ratio. The regression coefficient between the pelvic rotation angle and the LSI of the knee-to-support moment ratio was comparable to the LSI of the AP-COP position, which has been reported to be useful for predicting the interlimb asymmetry of hip-to-knee and ankle-to-knee extensor moment ratios during double-leg squatting after ACLR.[2] Based on these findings, an assessment of pelvic rotation would be useful to partially predicting the asymmetry in the knee extensor moment and its contribution during double-leg squatting.

The regression equations used to predict the LSI of the knee extensor moment and knee-to-support moment ratio by the pelvic rotation angle indicate that regression lines pass close to the intersection of the symmetrical lines, i.e., the point where the LSIs of the knee extensor moment and the knee-to-support moment ratio are 100% and the pelvic rotation angle is 0° (Figures 3a and 4a). These relationships also supported the hypothesis that the pelvic rotation angle is useful to predict the interlimb asymmetry in the knee extensor moment and knee-to-support moment ratio during double-leg squatting. Pelvic rotation could be assessed by determining to which side the pelvis is rotated, and instructions will be provided to lead to neutral pelvic rotation. Previous studies did not report an interlimb difference in the knee flexion angle during double-leg squatting after ACLR, although a significant interlimb difference in the knee extensor moment was observed.[6,7] Therefore, a visual assessment of small interlimb differences may be difficult. The assessment of pelvic rotation may be useful to predict the interlimb asymmetry in the knee extensor moment and knee-to-support moment ratio in a clinical setting.

The causality of the association between knee extensor moment asymmetry and pelvic rotation was not determined in the present study. Although a significant linear association was not observed between the pelvic rotation angle and LSI of the VGRF or AP-COP position, pelvic rotation may result from altered lower-limb muscle activity. After ACLR, individuals increase the demand on the hip extensor (e.g., gluteus maximus) but decrease the demand on the quadriceps,[2-4,6,7] and the altered hip muscle activity may have affected pelvic kinematics.

A previous study examined the effect of trunk rotation by healthy individuals during double-leg landing.[29] Although this previous study did not examine the distribution of hip, knee, and ankle extensor moments, the knee extensor moment relative to VGRF seems smaller when the landing with ipsilateral rotation compared with landing with contralateral rotation. The results of the present study may support these findings. The relationship between pelvic rotation and lower extremity kinetic asymmetry has not been investigated during double-leg landing and should be examined in future studies.

The pelvic rotation angle explained 38% of the variance in the LSI of the knee extensor moment at peak knee flexion and 24% for the variance at the mean value. The interlimb asymmetry in the knee extensor moment was associated with both the asymmetry in VGRF and load distribution among hip, knee, and ankle joints.[2,4] The assessment of pelvic rotation was designed to predict the asymmetry in the load distribution. Therefore, combining the pelvic rotation angle and the LSI of the VGRF improved the explanation of variance in the LSI of the knee extensor moment to 61% at both peak knee flexion and the mean value. For a better prediction, pelvic rotation and the symmetry of the VGRF might be considered.

The LSI of the AP-COP position significantly predicted the LSI of the knee-to-support moment. This result supports previous findings that the LSI of the AP-COP position significantly predicted the LSI of the hip-to-knee and ankle-to-knee extensor moment ratios during double-leg squatting after ACLR.[2] The relationship between the AP-COP position and the knee-to-support moment ratio was also reported for healthy individuals.[18,30] However, the present study did not detect a significant association between the LSI of the AP-COP position and knee extensor moment, which is inconsistent with a previous study.[2] A possible explanation may be that the patients in this previous study were in the early postoperative period and had larger asymmetry in the knee extensor moment.[2] An assessment of the AP-COP position would be useful for predicting asymmetry in the load distribution among the joints.[18] Pelvic rotation may be a more sensitive measure to detect asymmetry in the knee extensor moment compared with the AP-COP position.

A double-leg squat is a basic exercise that is commonly used for quadriceps strength training in rehabilitation after ACLR.[1] Co-contraction of the quadriceps with the hamstrings results in minimal or no ACL tensile force during a squatting exercise.[31] Therefore, a smaller knee extensor moment during a squatting exercise has an advantage in terms of protecting graft healing, especially in the early postoperative phase. However, knee extensor moment deficits during double-leg squatting are observed not only in the early postoperative phase but also more than one year after surgery.[3,7] The effect of squatting exercises on strengthening quadriceps may be limited by compensatory mechanisms, and these altered motor controls may prevent the recovery of quadriceps muscle strength.[3,6,7,32] Deficits in quadriceps strength are problematic not only in the early postoperative phase but also two years or more after surgery.[10] An assessment of and feedback on the pelvic rotation during squatting may be useful for modifying the interlimb asymmetry in knee extensor moment and its contribution during double-leg squatting. Trunk and pelvic control have been areas of focus in ACL injury and reinjury prevention.[33-35] Jump-landing training with verbal instructions reduced the lateral trunk lean and knee abduction moment during single-leg landing.[36] Therefore, pelvic rotation might also be improved with movement training using verbal instructions. However, the assessment of small pelvic rotation angles may require three-dimensional motion analysis. Further studies are needed to clarify clinically valid assessments and the effect of feedback training to maintain neutral pelvic rotation during double-leg squatting on the knee extensor moment and its contribution.

The present findings should be generalized with caution. First, the results from the early postoperative period may differ from those of the present study due to the use of different compensatory strategies. Further studies examining patients in the early postoperative period, as well as the effect of interventions to modify pelvic rotation, are needed. Second, the present study examined only double-leg squatting. The association between pelvic rotation and knee extensor moment during single-leg squatting may be different from the findings of the present study because one foot is not fixed during single-leg squatting. Moreover, further research is needed to determine if the present findings can be applied to more dynamic tasks such as double-leg landing.

The present study had some limitations. First, this study did not include a control group. Second, skin movement may affect the calculation of pelvic motion in the marker-based motion analysis system, which would affect the present results. Finally, the rehabilitation program and period were not controlled among participants.

In conclusion, pelvic rotation toward the involved limb was associated with a smaller knee extensor moment and knee-to-support moment ratio in the involved limb than in the uninvolved limb during double-leg squatting after ACLR. The pelvic rotation angle explained 38% of the variance in the LSI of the knee extensor moment and 64% when combined with the LSI of VGRF. Moreover, the pelvic rotation angle alone explained 40% of the variance in the

LSI of the knee-to-support moment ratio and 60% when combined with the LSI of the AP-COP position. The assessment of pelvic rotation in the horizontal plane would be useful to partially predict the asymmetry in the knee extensor moment and knee-to-support moment ratio in a clinical setting, and interventions designed to modify pelvic rotation may improve the asymmetry in the knee extensor moment during double-leg squatting after ACLR.

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References

1. van Melick N, van Cingel REH, Brooijmans F, et al. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *Br J Sports Med*. 2016;50(24):1506-1515. doi:10.1136/bjsports-2015-095898
2. 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
3. Webster KE, Austin DC, Feller JA, Clark RA, McClelland JA. Symmetry of squatting and the effect of fatigue following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(11):3208-3213. doi:10.1007/s00167-014-3121-3
4. Sigward SM, Chan M-SM, Lin PE, Almansouri SY, Pratt KA. Compensatory Strategies That Reduce Knee Extensor Demand During a Bilateral Squat Change From 3 to 5 Months Following Anterior Cruciate Ligament Reconstruction. *J Orthop Sports Phys Ther*. 2018;48(9):713-718. doi:10.2519/jospt.2018.7977
5. Sanford BA, Williams JL, Zucker-Levin A, Mihalko WM. Asymmetric ground reaction

forces and knee kinematics during squat after anterior cruciate ligament (ACL) reconstruction. *Knee*. 2016;23(5):820-825. doi:10.1016/j.knee.2015.11.001

6. Salem GJ, Salinas R, Harding FV. Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2003;84(8):1211-1216. doi:10.1016/s0003-9993(03)00034-0
7. Roos PE, Button K, van Deursen RWM. Motor control strategies during double leg squat following anterior cruciate ligament rupture and reconstruction: an observational study. *J Neuroeng Rehabil*. 2014;11:19. doi:10.1186/1743-0003-11-19
8. Ogborn D. Optimizing Exercise Selection for the Asymmetric Athlete After Anterior Cruciate Ligament Reconstruction. *Strength and Conditioning Journal*. 2021;43(4):105-114. doi:10.1519/SSC.0000000000000605
9. Peebles AT, Williams B, 3rd, Queen RM. Bilateral Squatting Mechanics Are Associated With Landing Mechanics in Anterior Cruciate Ligament Reconstruction Patients. *Am J Sports Med*. 2021;49(10):2638-2644. doi:10.1177/03635465211023761
10. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. *Arch Orthop Trauma Surg*. 2014;134(10):1417-1428. doi:10.1007/s00402-014-1992-x
11. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. 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
12. 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

13. Hannon JP, Goto S, Singleton S, et al. Effects of anterior cruciate ligament reconstruction on patellofemoral joint stress and lower extremity biomechanics at 12 weeks post-surgery and at time of return to sport in adolescent females. *Clin Biomech (Bristol, Avon)*. 2020;80:105164. doi:10.1016/j.clinbiomech.2020.105164
14. Hall M, Stevermer CA, Gillette JC. Gait analysis post anterior cruciate ligament reconstruction: knee osteoarthritis perspective. *Gait Posture*. 2012;36(1):56-60. doi:10.1016/j.gaitpost.2012.01.003
15. Shimizu T, Samaan MA, Tanaka MS, et al. Abnormal Biomechanics at 6 Months Are Associated With Cartilage Degeneration at 3 Years After Anterior Cruciate Ligament Reconstruction. *Arthroscopy*. 2019;35(2):511-520. doi:10.1016/j.arthro.2018.07.033
16. Verstegen M, Falsone S, Orr R, Smith S. Suggestions from the field for return to sports participation following anterior cruciate ligament reconstruction: American football. *J Orthop Sports Phys Ther*. 2012;42(4):337-344. doi:10.2519/jospt.2012.4031
17. Chmielewski TL. Asymmetrical lower extremity loading after ACL reconstruction: more than meets the eye. *J Orthop Sports Phys Ther*. 2011;41(6):374-376. doi:10.2519/jospt.2011.0104
18. 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 science, medicine & rehabilitation*. 2022;14(1):127. doi:10.1186/s13102-022-00523-0
19. 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*. 2021:1-11. doi:10.1080/15438627.2021.1966010
20. Webster KE, Hewett TE. What is the Evidence for and Validity of Return-to-Sport Testing

after Anterior Cruciate Ligament Reconstruction Surgery? A Systematic Review and Meta-Analysis. *Sports Medicine (Auckland, NZ)*. 2019;49(6):917-929. doi:10.1007/s40279-019-01093-x

21. McClelland JA, Webster KE, Grant C, Feller J. Alternative modelling procedures for pelvic marker occlusion during motion analysis. *Gait Posture*. 2010;31(4):415-419. doi:10.1016/j.gaitpost.2010.01.004
22. Bell AL, Brand RA, Pedersen DR. Prediction of hip joint centre location from external landmarks. *Hum Mov Sci*. 1989;8(1):3-16. doi:10.1016/0167-9457(89)90020-1
23. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *J Biomech*. 1996;29(9):1223-1230. doi:10.1016/0021-9290(95)00178-6
24. Song Y, Li L, Albrandt EE, Jensen MA, Dai B. Medial-lateral hip positions predicted kinetic asymmetries during double-leg squats in collegiate athletes following anterior cruciate ligament reconstruction. *J Biomech*. 2021;128:110787. doi:10.1016/j.jbiomech.2021.110787
25. Jean LMY, Chiu LZF. Elevating the Noninvolved Limb Reduces Knee Extensor Asymmetry During Squat Exercise in Persons With Reconstructed Anterior Cruciate Ligament. *J Strength Cond Res*. 2020;34(8):2120-2127. doi:10.1519/jsc.0000000000003682
26. 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
27. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Medicine (Auckland, NZ)*. 2000;30(1):1-15. doi:10.2165/00007256-200030010-00001
28. Ithurburn MP, Paterno MV, Thomas S, et al. Change in Drop-Landing Mechanics Over 2 Years in Young Athletes After Anterior Cruciate Ligament Reconstruction. *Am J Sports*

Med. 2019;47(11):2608-2616. doi:10.1177/0363546519864688

29. Critchley ML, Davis DJ, Keener MM, et al. The effects of mid-flight whole-body and trunk rotation on landing mechanics: implications for anterior cruciate ligament injuries. *Sports Biomech*. 2020;19(4):421-437. doi:10.1080/14763141.2019.1595704
30. 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. *Journal of Sports Science and Medicine*. 2022;21(3):341-346.
31. Escamilla RF, Macleod TD, Wilk KE, Paulos L, Andrews JR. Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: a guide to exercise selection. *J Orthop Sports Phys Ther*. 2012;42(3):208-220. doi:10.2519/jospt.2012.3768
32. Garrison JC, Hannon J, Goto S, Giesler L, Bush C, Bothwell JM. Participants at three months post-operative anterior cruciate ligament reconstruction (ACL-R) demonstrate differences in lower extremity energy absorption contribution and quadriceps strength compared to healthy controls. *Knee*. 2018;25(5):782-789. doi:10.1016/j.knee.2018.06.014
33. Kawashima T, Omi Y, Kuriyama S, Hoshida T, Sugimoto D. Effect of Graft Rupture Prevention Training on Young Athletes After Anterior Cruciate Ligament Reconstruction: An 8-Year Prospective Intervention Study. *Orthopaedic Journal of Sports Medicine*. 2021;9(1):2325967120973593. doi:10.1177/2325967120973593
34. Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med*. 2008;27(3):425-448, ix. doi:10.1016/j.csm.2008.02.006
35. Omi Y, Sugimoto D, Kuriyama S, et al. Effect of Hip-Focused Injury Prevention Training for Anterior Cruciate Ligament Injury Reduction in Female Basketball Players: A 12-Year Prospective Intervention Study. *Am J Sports Med*. 2018;46(4):852-861.

doi:10.1177/0363546517749474

36. Chijimatsu M, Ishida T, Yamanaka M, et al. Landing instructions focused on pelvic and trunk lateral tilt decrease the knee abduction moment during a single-leg drop vertical jump. *Phys Ther Sport*. 2020;46:226-233. doi:https://doi.org/10.1016/j.ptsp.2020.09.010

Table 1 Characteristics of the participants (N = 24)

Characteristic	Value
Age, years	22.0 (1.8)
Height, cm	166.4 (7.3)
Weight, kg	58.4 (8.2)
Sex	7 male/17 female
Time since surgery, years	4.5 (2.7)
LSI of the knee extensor strength, %	96.0 (15.7)
Knee extensor strength deficit (LSI < 90%), n	9 (38%)

Means (SD) are reported for all values, except for sex and the knee extensor strength deficit, which are reported as numbers.
LSI: limb symmetry index

Table 2. Results from multivariate regression models used to predict the LSI of the knee extensor moment

	B (95%CI)	*β*	*p*
At peak knee flexion			
LSI of VGRF, %	1.133 (0.522, 1.743)	0.524	< .001
Pelvic rotation angle, °	−3.984 (−6.284, −1.684)	−0.489	.002
Mean value			
LSI of VGRF, %	1.272 (0.676, 1.867)	0.620	< .001
Pelvic rotation angle, °	−3.191 (−5.747, −0.635)	−0.362	.017

LSI: limb symmetry index

VGRF: vertical ground reaction force

Table 3. Results from multivariate regression models used to predict the LSI of the knee-to-support moment ratio

	B (95%CI)	*β*	*p*
At peak knee flexion			
Pelvic rotation angle, °	−3.414 (−5.627, −0.120)	−0.474	.004
LSI of AP-COP position, %	−0.498 (−0.826, −1.171)	−0.467	.005
Mean value			
Pelvic rotation angle, °	−2.623 (−5.157, −0.090)	−0.389	.043
LSI of AP-COP position, %	−0.433 (−0.853, −0.014)	−0.388	.044

LSI: limb symmetry index

AP-COP: anterior-posterior center-of-pressure

Figure Captions

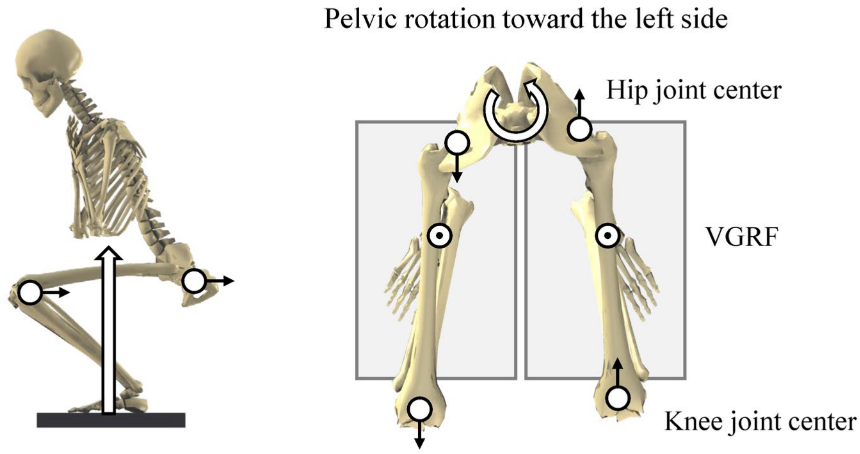

Figure 1 Schema of the changes in the relationship between the ground reaction force vector (GRF) and the hip and knee joint center accompanied by pelvic rotation toward the left (sagittal and top views). White circles with black arrows represent anterior or posterior shifts of the left hip and knee joint. As a result of pelvic rotation toward the left, the left knee joint center would approach the GRF, while the left hip joint center would move away from the GRF. Thus, the distance between the left knee joint and the GRF would be shortened, and the distance between the left hip joint and the GRF would be lengthened compared with the neutral rotation of the pelvis.

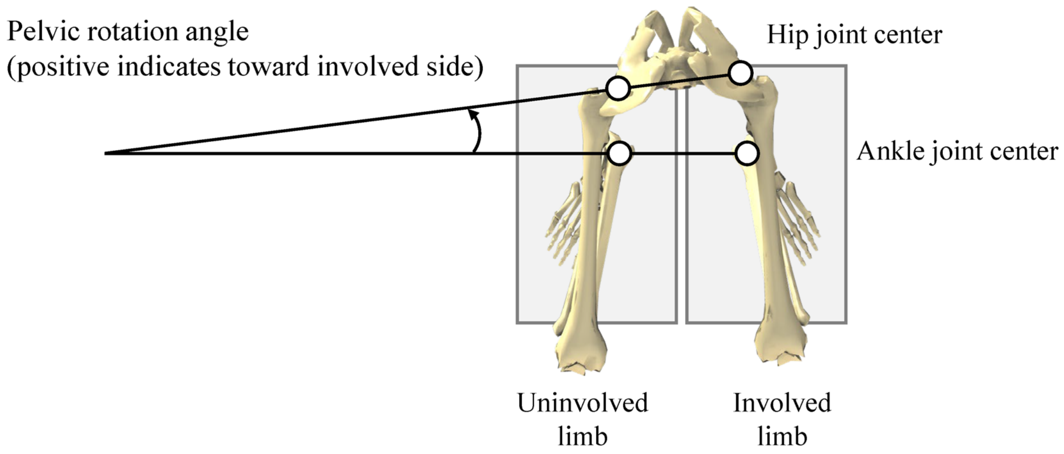

Figure 2 Pelvic rotation angle in the horizontal plane.

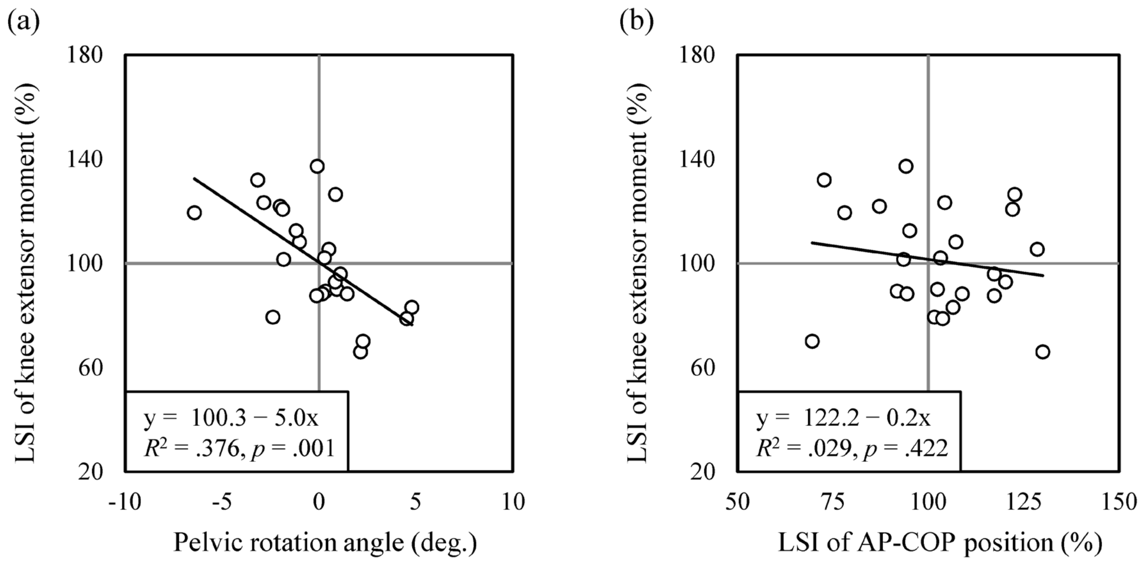

Figure 3. Relationship between the limb symmetry index (LSI) of the knee extensor moment and pelvic rotation angle (a), the LSI of the anterior-posterior center-of-pressure (AP-COP) position (b). Vertical and horizontal lines indicate symmetry (LSI = 100% or pelvic rotation angle = 0°).

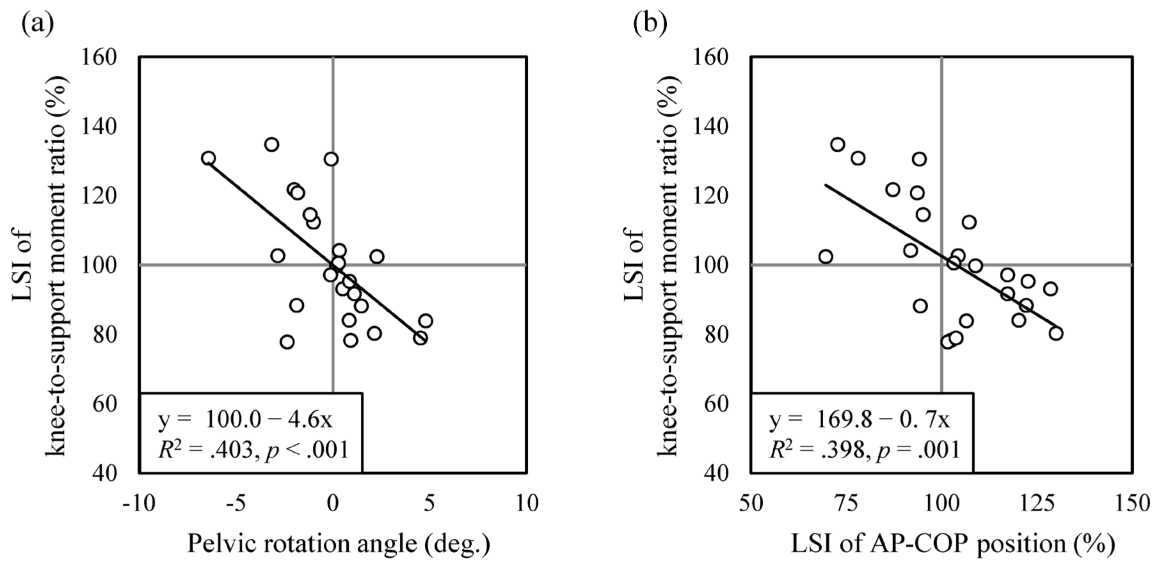

Figure 4. Relationship between the limb symmetry index (LSI) of the knee-to-support moment ratio and pelvic rotation angle (a) and the LSI of the anterior-posterior center-of-pressure (AP-COP) position (b). Vertical and horizontal lines indicate symmetry (LSI = 100% or pelvic rotation angle = 0°).