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Title	Pelvic Rotation Is Associated With Asymmetry in the Knee Extensor Moment During Double-Leg Squatting After Anterior Cruciate Ligament Reconstruction
Author(s)	Ishida, Tomoya; Samukawa, Mina; Koshino, Yuta; Ino, Takumi; Kasahara, Satoshi; Tohyama, Harukazu
Citation	Journal of Applied Biomechanics, 39(1), 62-68 https://doi.org/10.1123/jab.2022-0204
Issue Date	2023-02-01
Doc URL	http://hdl.handle.net/2115/89120
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Туре	article (author version)
File Information	Ishida2023.pdf



JAB.2022-0204.R2

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

Tomoya Ishida^{1*}, Mina Samukawa¹, Yuta Koshino¹, Takumi Ino², Satoshi Kasahara¹, Harukazu Tohyama¹

¹Faculty of Health Sciences, Hokkaido University, Sapporo, Japan.
²Faculty of Health Sciences, Hokkaido University of Science, Sapporo, Japan.

Conflict of Interest Disclosure: None.

*Corresponding Address:

Tomoya Ishida Faculty of Health Sciences, Hokkaido University North 12, West 5, Kitaku Sapporo 060-0812, Japan. E-mail: t.ishida@hs.hokudai.ac.jp Phone & Fax: +81-11-706-3531

Running Title: Pelvic rotation and knee moment asymmetry

1 Abstract

Asymmetry in knee extensor moment during double-leg squatting was observed after anterior $\mathbf{2}$ 3 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 4 asymmetry in the knee extensor moment and pelvic rotation angle during double-leg squatting $\mathbf{5}$ 6 after ACLR. Twenty-four participants performed double-leg squatting. Kinetics and kinematics $\overline{7}$ during squatting were analyzed using a three-dimensional motion analysis system with two 8 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 9 10 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 11 12toward 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 13partially predicting asymmetry in the knee extensor moment during double-leg squatting. 14Minimizing pelvic rotation may improve the asymmetry in the knee extensor moment during 15double-leg squatting after ACLR. 16

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18 Keywords: compensation, knee extension moment, quadriceps, motor control, rehabilitation
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20 Word count: 3997 words (four figures and three tables)

Introduction

Double-leg squatting is commonly used as a basic exercise to improve lower-limb 23joint control after anterior cruciate ligament reconstruction (ACLR),¹⁻⁸ whereas the knee 2425extensor 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 26extensor moment may limit the effectiveness of exercise.^{3,6-8} Quadriceps weakness in the 27involved limb can be observed for more than 2 years and up to 5 years after surgery.¹⁰ 28Moreover, asymmetry in the knee extensor moment during double-leg squatting is 29positively and moderately correlated with that during the landing task after ACLR.⁹ An 30improvement in the asymmetry in the knee extensor moment during double-leg squatting 31may translate to improved symmetry in the knee extensor moment during double-leg 32landing.9 A second ACL injury occurs in 15% of patients,11 while asymmetry in knee 33extensor moment during double-leg landing is a risk factor of second injury.¹² Additionally, 34although comprehensive mechanism has not been elucidated, the decreased knee loading 3536 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⁻ 37¹⁵ Therefore, an improvement in asymmetry of the knee extensor moment during weight 38 bearing activities, including double-leg squatting, is targeted throughout the rehabilitation 39process for return to sports.^{8,16,17} However, asymmetry in the knee extensor moment during 40 41double-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 42the asymmetry of the knee extensor moment in double-leg squatting or other weight-43bearing activities.⁸ 44

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

47the 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 48to the hip, ankle or support moment is significantly smaller in the involved limb than in the 49uninvolved limb.^{2,4,7} Asymmetry in the knee extensor moment after ACLR was observed 50even in individuals demonstrating a symmetrical VGRF or support moment during double-51leg squatting.^{6,7} Asymmetry in the contribution of knee extensor moment is related to 52asymmetry in the knee extensor moment in the long term compared to the asymmetry in 53VGRF.⁴ An improvement in asymmetry in the contribution of the knee extensor moment is 5455needed to restore a symmetrical knee extensor moment during double-leg squatting after ACLR. 56

Asymmetry in the anterior-posterior (AP) center-of-pressure (COP) position is 57associated with asymmetry in hip-to-knee and ankle-to-knee extensor moment ratios 58during double-leg squatting after ACLR.² Asymmetry in the AP-COP position is also 59associated with asymmetry in the knee-to-support moment ratio of healthy individuals 60 during double-leg squatting.¹⁸ These findings suggest that the AP-COP position is 61 associated with distribution among hip, knee, and ankle extensor moments during double-62leg squatting. Changes in the AP-COP position are proposed to affect lower-limb joint 63 moments in the sagittal plane by altering the distance between the VGRF vectors and the 64 lower-limb joint centers.^{2,18} On the other hand, changes in each lower limb joint position 65 66in 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 67changes in the AP-COP position. However, asymmetry in the lower limb kinematics is not 68 associated with asymmetry in the knee extensor moment during double-leg squatting.¹⁸ 69 Pelvic rotation in the horizontal plane may result in anterior or posterior shifts of the knee 70and hip joint centers during the double-leg squatting with both feet fixed to the ground 71

(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 7980 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. 81 The hypothesis was that the pelvic rotation toward the involved side would be associated 82 83 with a smaller knee extensor moment and knee-to-support moment ratio in the involved 84 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 85 in the knee extensor moment. 86

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Methods

Participants: The present study enrolled 24 participants (Table 1). A prior sample size 89 calculation showed that 21 participants were needed to achieve an alpha level (α), statistical 90 power $(1 - \beta)$ and a regression coefficient of 0.05, 0.8, and 0.3 respectively. The assumption 91of a correlation coefficient was based on a previous study showing the relationship between 92the interlimb asymmetries in the AP-COP position and knee extensor moment.² The 93 94inclusion 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 95had undergone bilateral or revision ACLR or had a history of knee injuries in the involved 96

97or uninvolved limb except for primary ACLR. Written informed consent was obtained from each participant before participation. This study was approved by the Institutional Review 98 Board of the Faculty of Health Sciences, Hokkaido University (approval number: 19-72). 99100 Procedures: A five-minute warm-up was performed with a stationary bicycle 101ergometer 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, 102103respectively), lateral thigh, medial and lateral femoral epicondyle, lateral shank, medial and lateral malleoli, second metatarsal head and base, fifth metatarsal head and heel. First, 104105a 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 106 107one foot on an individual force plate and arms crossed over their chest. They were asked 108 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 109 possible without their heels coming off the floor. A metronome was used to help 110participants squat for 2 seconds each for descent and ascent.³ The participants were allowed 111 to rest between each trial as needed. The rest time was usually two to three minutes. 112

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.

118 Knee extensor strength was tested after biomechanical experiments to characterize 119 the participants. Isokinetic concentric torque at $60^{\circ} \cdot s^{-1}$ was assessed with a dynamometer 120 (Biodex System 3, Biodex Medical Systems, Inc., Shirley, NY) using a previously 121 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 124(version 6, C-Motion, Inc., Germantown, MD, USA) and MATLAB 2021b (MathWorks, 125Inc., Natick, MA, USA). Marker trajectories and force plate data were low-pass filtered 126using a fourth-order, zero-lag Butterworth filter with a 12-Hz cutoff frequency.^{2,4} When the 127ASIS markers were missing during the squatting task, iliac crest and PSIS markers were 128used to fill ASIS marker trajectory gaps.²¹ The hip joint center was estimated based on a 129previous study,²² while the knee and ankle joint centers were calculated as the midpoint 130between the medial and lateral epicondyles, and between the medial and lateral malleoli, 131respectively. Hip, knee, and ankle joint angles and moments were calculated using a joint 132133coordinate 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 134knee-to-support moment ratio was calculated, and the support moment was calculated as 135the sum of the hip, knee, and ankle extensor moments.⁷ The pelvic rotation angle was 136calculated as the angle between the bilateral hip joint line and ankle joint line on the 137horizontal plane (Figure 2). A positive angle indicates rotation toward the involved side. In 138addition, the AP-COP position of each foot was calculated. The AP-COP direction was 139adjusted by the vector from the heel marker to the 2nd metatarsal head marker.² The AP-140141COP 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 142 $(100\%)^2$ 143

144 The analysis was conducted at the peak knee flexion angle during squatting because 145 the knee extensor moment and asymmetry in the knee extensor moment were the largest at 146 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). 157In addition, the number of participants showing an LSI of knee extensor moment less than 15890% was reported.²⁸ A statistical analysis was performed for each of the values at peak 159knee flexion and the mean values. A univariate regression analysis was performed to 160161examine the linear relationship between the LSI of the knee extensor moment and knee-tosupport moment ratio, and the pelvic rotation angle and the LSI of the AP-COP position. 162Moreover, a stepwise regression analysis was conducted to determine the independent 163predictive ability of the pelvic rotation angle, the LSI of the AP-COP position and the 164165VGRF for the LSI of the knee extensor moment and knee-to-support moment ratio. The 166final regression model was determined based on the minimum Akaike information criterion. 167Additionally, 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 168169statistical significance level was set to p < .05. These statistical analyses were performed using JMP Pro software (version 15, SAS Institute Inc., Cary, NC, USA). 170

Results

The LSI of the knee extensor moment at peak knee flexion was $100.8 \pm 19.9\%$, and 173nine participants (38%) showed an LSI less than 90%. Meanwhile, the LSI of the mean 174knee extensor moment during knee flexion at angles larger than 60° was $100.2 \pm 19.1\%$. 175and eight participants (33%) showed an LSI less than 90%. The pelvic rotation angle was 176 $-0.1 \pm 2.4^{\circ}$ (maximum: 4.8°, minimum: -6.4°) at peak knee flexion and $-0.1 \pm 2.2^{\circ}$ 177(maximum: 5.1° , minimum: -5.2°) for the mean value. The SDs of pelvic rotation angles 178among trials within each participant were $1.3 \pm 0.5^{\circ}$ at peak knee flexion and $1.1 \pm 0.5^{\circ}$ for 179180the 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-181COP position (Figure 3b). Pelvic rotation toward the involved limb was associated with a 182183smaller 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 184rotation angle explained 63% of the variance in the LSI of the knee extensor moment 185(model $R^2 = .635$, p < .001) (Table 2). The LSI of the AP-COP position was not included 186 in the multivariate model. The LSI of the mean knee extensor moment was also predicted 187by the mean pelvic rotation angle ($R^2 = .242$, B = -4.3, intercept = 99.6, P = .015). The 188 stepwise regression analysis showed that the LSIs of the mean VGRF and the mean pelvic 189rotation angle were significant predictors of the LSI of the mean knee extensor moment 190(model $R^2 = .609, p < .001$) (Table 2). 191

The LSI of the knee-to-support moment ratio was $100.5 \pm 17.6\%$ at peak knee flexion and $98.6 \pm 14.6\%$ 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 ($R^2 = .398$, 197p = .001) (Figure 4b). In the multivariate regression analysis, the LSI of the knee-to-support 198moment ratio was predicted by the pelvic rotation angle and the LSI of the AP-COP 199position (model $R^2 = .596$, p < .001) (Table 3). The LSI of the mean knee-to-support 200 moment ratio was also predicted by the mean pelvic rotation angle ($R^2 = .293$, B = -3.7, 201intercept = 98.1, p = .006) and the LSI of the mean AP-COP position ($R^2 = .293$, B = -0.6, 202intercept = 161.6, p = .006). The stepwise regression analysis showed that the mean pelvic 203rotation angle and LSIs of the AP-COP position were significant predictors of the LSI of 204the mean knee-to-support moment ratio (model $R^2 = .421$, p = .003) (Table 3). 205

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).

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Discussion

The present study revealed that the pelvic rotation angle predicted the asymmetry in the 212knee extensor moment and knee-to-support moment ratio during double-leg squatting in 213individuals who underwent ACLR. To our knowledge, this study is the first to report the 214215association between the pelvic rotation angle and the asymmetry in the knee extensor moment 216and 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 217knee extensor moment at the peak knee flexion and 61% of the variance at the mean value, and 218219the 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 220the variance at the mean value. These results supported the a priori hypothesis. 221

During double-leg squatting, both feet are fixed to the ground. Therefore, the pelvic 222rotation toward the involved limb would lead to a posterior shift of the hip and knee joints on 223the involved side (Figure 1). Consistent with our hypothesis, pelvic rotation toward the 224225involved 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 226extensor moment would result from the redistribution among hip, knee, and ankle extensor 227228moments 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 229230between 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 231predicting the interlimb asymmetry of hip-to-knee and ankle-to-knee extensor moment ratios 232during double-leg squatting after ACLR.² Based on these findings, an assessment of pelvic 233rotation would be useful to partially predicting the asymmetry in the knee extensor moment 234and its contribution during double-leg squatting. 235

The regression equations used to predict the LSI of the knee extensor moment and knee-236to-support moment ratio by the pelvic rotation angle indicate that regression lines pass close to 237the intersection of the symmetrical lines, i.e., the point where the LSIs of the knee extensor 238moment and the knee-to-support moment ratio are 100% and the pelvic rotation angle is 0° 239240(Figures 3a and 4a). These relationships also supported the hypothesis that the pelvic rotation 241angle is useful to predict the interlimb asymmetry in the knee extensor moment and knee-to-242support 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 243244neutral 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 245difference in the knee extensor moment was observed.^{6,7} Therefore, a visual assessment of 246

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 263moment at peak knee flexion and 24% for the variance at the mean value. The interlimb 264asymmetry in the knee extensor moment was associated with both the asymmetry in VGRF 265and load distribution among hip, knee, and ankle joints.^{2,4} The assessment of pelvic rotation 266was designed to predict the asymmetry in the load distribution. Therefore, combining the pelvic 267rotation angle and the LSI of the VGRF improved the explanation of variance in the LSI of the 268269knee 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. 270

271The 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 272significantly predicted the LSI of the hip-to-knee and ankle-to-knee extensor moment ratios 273during double-leg squatting after ACLR.² The relationship between the AP-COP position and 274the knee-to-support moment ratio was also reported for healthy individuals.^{18,30} However, the 275present study did not detect a significant association between the LSI of the AP-COP position 276and knee extensor moment, which is inconsistent with a previous study.² A possible explanation 277may be that the patients in this previous study were in the early postoperative period and had 278larger asymmetry in the knee extensor moment.² An assessment of the AP-COP position would 279be useful for predicting asymmetry in the load distribution among the joints.¹⁸ Pelvic rotation 280may be a more sensitive measure to detect asymmetry in the knee extensor moment compared 281282with the AP-COP position.

A double-leg squat is a basic exercise that is commonly used for quadriceps strength 283training in rehabilitation after ACLR.¹ Co-contraction of the quadriceps with the hamstrings 284results in minimal or no ACL tensile force during a squatting exercise.³¹ Therefore, a smaller 285knee extensor moment during a squatting exercise has an advantage in terms of protecting graft 286healing, especially in the early postoperative phase. However, knee extensor moment deficits 287during double-leg squatting are observed not only in the early postoperative phase but also 288more than one year after surgery.^{3,7} The effect of squatting exercises on strengthening 289290quadriceps 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 291problematic not only in the early postoperative phase but also two years or more after surgery.¹⁰ 292293An 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 294double-leg squatting. Trunk and pelvic control have been areas of focus in ACL injury and 295

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 303 304postoperative 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, 305as well as the effect of interventions to modify pelvic rotation, are needed. Second, the present 306307 study examined only double-leg squatting. The association between pelvic rotation and knee 308 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 309 310 needed to determine if the present findings can be applied to more dynamic tasks such as 311double-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

321	LSI of the knee-to-support moment ratio and 60% when combined with the LSI of the AP-COP
322	position. The assessment of pelvic rotation in the horizontal plane would be useful to partially
323	predict the asymmetry in the knee extensor moment and knee-to-support moment ratio in a
324	clinical setting, and interventions designed to modify pelvic rotation may improve the
325	asymmetry in the knee extensor moment during double-leg squatting after ACLR.
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327	Acknowledgments
328	This work was supported by JSPS KAKENHI (Grant Number JP20K19477).
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- 451

452 **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%)

453 Means (SD) are reported for all values, except for sex and the knee extensor strength deficit,

454 which are reported as numbers.

455 LSI: limb symmetry index

 $\begin{array}{c} 456 \\ 457 \end{array}$

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

extensor moment

	<i>B</i> (95%CI)	β	р	
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

	<i>B</i> (95%CI)	β	р
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 1 Schema of the changes in the relationship between the ground reaction force 471472vector (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 473shifts of the left hip and knee joint. As a result of pelvic rotation toward the left, the left 474knee joint center would approach the GRF, while the left hip joint center would move away 475from the GRF. Thus, the distance between the left knee joint and the GRF would be 476shortened, and the distance between the left hip joint and the GRF would be lengthened 477compared with the neutral rotation of the pelvis. 478





481 **Figure 2** Pelvic rotation angle in the horizontal plane.



483

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°).

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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°).