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

Tomoya Ishida<sup>1\*</sup>, Mina Samukawa<sup>1</sup>, Yuta Koshino<sup>1</sup>, Takumi Ino<sup>2</sup>,  
Satoshi Kasahara<sup>1</sup>, Harukazu Tohyama<sup>1</sup>

<sup>1</sup>Faculty of Health Sciences, Hokkaido University, Sapporo, Japan.

<sup>2</sup>Faculty of Health Sciences, Hokkaido University of Science, Sapporo, Japan.

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**\*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](mailto:t.ishida@hs.hokudai.ac.jp)

Phone & Fax: +81-11-706-3531

**Running Title:** Pelvic rotation and knee moment asymmetry

1

1 **Abstract**

2 Asymmetry in knee extensor moment during double-leg squatting was observed after anterior  
3 cruciate ligament reconstruction (ACLR), even after the completion of the rehabilitation  
4 program for return to sports. The purpose of this study was to clarify the association between  
5 asymmetry in the knee extensor moment and pelvic rotation angle during double-leg squatting  
6 after ACLR. Twenty-four participants performed double-leg squatting. Kinetics and kinematics  
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  
9 pelvic rotation angle ( $R^2 = .376, p = .001$ ). Additionally, the pelvic rotation and the LSI of the  
10 vertical ground reaction force (VGRF) independently explained the LSI of the knee extensor  
11 moment ( $R^2 = .635, p < .001, \beta$  of pelvic rotation =  $-0.489, \beta$  of VGRF =  $0.524$ ). Pelvic rotation  
12 toward the involved limb was associated with a smaller knee extensor moment in the involved  
13 limb than in the uninvolved limb. The assessment of pelvic rotation would be useful for  
14 partially predicting asymmetry in the knee extensor moment during double-leg squatting.  
15 Minimizing pelvic rotation may improve the asymmetry in the knee extensor moment during  
16 double-leg squatting after ACLR.

17

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

19

20 **Word count:** 3997 words (four figures and three tables)

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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),<sup>1-8</sup> 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.<sup>2-4,7,9</sup> The persistence of asymmetry in the knee extensor moment may limit the effectiveness of exercise.<sup>3,6-8</sup> Quadriceps weakness in the involved limb can be observed for more than 2 years and up to 5 years after surgery.<sup>10</sup> Moreover, asymmetry in the knee extensor moment during double-leg squatting is positively and moderately correlated with that during the landing task after ACLR.<sup>9</sup> 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.<sup>9</sup> A second ACL injury occurs in 15% of patients,<sup>11</sup> while asymmetry in knee extensor moment during double-leg landing is a risk factor of second injury.<sup>12</sup> 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.<sup>13-15</sup> 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.<sup>8,16,17</sup> 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.<sup>3,7</sup> No method has been established to improve the asymmetry of the knee extensor moment in double-leg squatting or other weight-bearing activities.<sup>8</sup>

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

47 the smaller contribution of the knee extensor moment relative to hip, ankle, and support  
48 moments in the involved limb.<sup>4,7</sup> The ratio of the contribution of the knee extensor moment  
49 to the hip, ankle or support moment is significantly smaller in the involved limb than in the  
50 uninvolved limb.<sup>2,4,7</sup> Asymmetry in the knee extensor moment after ACLR was observed  
51 even in individuals demonstrating a symmetrical VGRF or support moment during double-  
52 leg squatting.<sup>6,7</sup> Asymmetry in the contribution of knee extensor moment is related to  
53 asymmetry in the knee extensor moment in the long term compared to the asymmetry in  
54 VGRF.<sup>4</sup> An improvement in asymmetry in the contribution of the knee extensor moment is  
55 needed to restore a symmetrical knee extensor moment during double-leg squatting after  
56 ACLR.

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

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

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

87

## 88 **Methods**

89 Participants: The present study enrolled 24 participants (Table 1). A prior sample size  
90 calculation showed that 21 participants were needed to achieve an alpha level ( $\alpha$ ), statistical  
91 power ( $1 - \beta$ ) and a regression coefficient of 0.05, 0.8, and 0.3 respectively. The assumption  
92 of a correlation coefficient was based on a previous study showing the relationship between  
93 the interlimb asymmetries in the AP-COP position and knee extensor moment.<sup>2</sup> The  
94 inclusion criteria were as follows: (1) primary unilateral ACLR, (2) no restriction for sport  
95 activities, and (3) no pain during double-leg squatting. Participants were excluded if they  
96 had undergone bilateral or revision ACLR or had a history of knee injuries in the involved

97 or uninvolved limb except for primary ACLR. Written informed consent was obtained from  
98 each participant before participation. This study was approved by the Institutional Review  
99 Board of the Faculty of Health Sciences, Hokkaido University (approval number: 19-72).

100 Procedures: A five-minute warm-up was performed with a stationary bicycle  
101 ergometer at a self-selected pace. After the warm-up, a total of 26 retroreflective markers  
102 were placed on the iliac crest, anterior and posterior superior iliac spines (ASISs and PSISs,  
103 respectively), lateral thigh, medial and lateral femoral epicondyle, lateral shank, medial  
104 and lateral malleoli, second metatarsal head and base, fifth metatarsal head and heel. First,  
105 a standardized static standing trial was recorded. Then, participants performed three trials  
106 of five consecutive double-leg squats. They stood with their feet shoulder-width apart, with  
107 one 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  
109 standing position.<sup>3</sup> If their heels were off the floor, they were asked to squat as deeply as  
110 possible without their heels coming off the floor. A metronome was used to help  
111 participants squat for 2 seconds each for descent and ascent.<sup>3</sup> The participants were allowed  
112 to rest between each trial as needed. The rest time was usually two to three minutes.

113 All data were recorded using a motion capture system (Cortex version 5.0.1, Motion  
114 Analysis Corp., Santa Rosa, CA, USA) with seven high-speed digital cameras (Hawk  
115 cameras, Motion Analysis Corp.) and two synchronized force plates (Type 9286, Kistler  
116 AG, Winterthur, Switzerland). The sampling rates were set to 200 Hz for the marker  
117 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  $60^{\circ}\cdot\text{s}^{-1}$  was assessed with a dynamometer  
120 (Biodex System 3, Biodex Medical Systems, Inc., Shirley, NY) using a previously  
121 described method.<sup>19</sup> The limb symmetry index (LSI) was calculated as the percentage of

122 the peak torque in the involved side to that in the uninvolved side. Nine of the participants  
123 were considered to have strength deficits ( $LSI < 90\%$ )<sup>20</sup> (Table 1).

124 Data analysis: Data processing and reduction were performed using Visual3D  
125 (version 6, C-Motion, Inc., Germantown, MD, USA) and MATLAB 2021b (MathWorks,  
126 Inc., Natick, MA, USA). Marker trajectories and force plate data were low-pass filtered  
127 using a fourth-order, zero-lag Butterworth filter with a 12-Hz cutoff frequency.<sup>2,4</sup> When the  
128 ASIS markers were missing during the squatting task, iliac crest and PSIS markers were  
129 used to fill ASIS marker trajectory gaps.<sup>21</sup> The hip joint center was estimated based on a  
130 previous study,<sup>22</sup> while the knee and ankle joint centers were calculated as the midpoint  
131 between the medial and lateral epicondyles, and between the medial and lateral malleoli,  
132 respectively. Hip, knee, and ankle joint angles and moments were calculated using a joint  
133 coordinate system with the Cardan X-Y-Z sequence. In calculating joint moments, the  
134 segment inertial parameters were set as described in a previous report.<sup>23</sup> Moreover, the  
135 knee-to-support moment ratio was calculated, and the support moment was calculated as  
136 the sum of the hip, knee, and ankle extensor moments.<sup>7</sup> The pelvic rotation angle was  
137 calculated as the angle between the bilateral hip joint line and ankle joint line on the  
138 horizontal plane (Figure 2). A positive angle indicates rotation toward the involved side. In  
139 addition, the AP-COP position of each foot was calculated. The AP-COP direction was  
140 adjusted by the vector from the heel marker to the 2nd metatarsal head marker.<sup>2</sup> The AP-  
141 COP position was calculated as the percentage of the foot length (% foot length), which  
142 was defined as the distance from the heel marker (0%) to the second metatarsal head marker  
143 (100%).<sup>2</sup>

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.<sup>24,25</sup> In addition, the mean values were calculated for the

147 phase in which the knee was flexed more than 60° to evaluated tendency across the  
148 squatting task because this phase is of clinical interest.<sup>26</sup> Interlimb asymmetry was assessed  
149 by calculating the LSI, which was calculated as the percentage of the involved limb to the  
150 uninvolved limb.<sup>2,4,18</sup> All variables were averaged across the middle three of the five  
151 consecutive squats of the three trials.<sup>4,18</sup>

152 The test-retest reliability of the pelvic rotation angle was assessed by calculating  
153 intraclass correlation coefficients (ICCs) and typical errors.<sup>27</sup> The retest was conducted for  
154 14 participants with a one-week interval. The ICCs (1, k) were .892 for the pelvis angle at  
155 peak knee flexion and .896 for the mean pelvis angle. Typical errors were 0.64° for the  
156 pelvis angle at peak knee flexion and 0.57° for the mean pelvis angle.

157 Statistical analysis: Data are presented as the means and standard deviations (SD).  
158 In addition, the number of participants showing an LSI of knee extensor moment less than  
159 90% was reported.<sup>28</sup> A statistical analysis was performed for each of the values at peak  
160 knee flexion and the mean values. A univariate regression analysis was performed to  
161 examine the linear relationship between the LSI of the knee extensor moment and knee-to-  
162 support moment ratio, and the pelvic rotation angle and the LSI of the AP-COP position.  
163 Moreover, a stepwise regression analysis was conducted to determine the independent  
164 predictive ability of the pelvic rotation angle, the LSI of the AP-COP position and the  
165 VGRF for the LSI of the knee extensor moment and knee-to-support moment ratio. The  
166 final regression model was determined based on the minimum Akaike information criterion.  
167 Additionally, the linear relationships between the pelvic rotation angle and the LSI of the  
168 VGRF, and the AP-COP position were confirmed using a linear regression analysis. The  
169 statistical significance level was set to  $p < .05$ . These statistical analyses were performed  
170 using JMP Pro software (version 15, SAS Institute Inc., Cary, NC, USA).

171

172

## Results

173           The LSI of the knee extensor moment at peak knee flexion was  $100.8 \pm 19.9\%$ , and  
174 nine participants (38%) showed an LSI less than 90%. Meanwhile, the LSI of the mean  
175 knee extensor moment during knee flexion at angles larger than  $60^\circ$  was  $100.2 \pm 19.1\%$ ,  
176 and eight participants (33%) showed an LSI less than 90%. The pelvic rotation angle was  
177  $-0.1 \pm 2.4^\circ$  (maximum:  $4.8^\circ$ , minimum:  $-6.4^\circ$ ) at peak knee flexion and  $-0.1 \pm 2.2^\circ$   
178 (maximum:  $5.1^\circ$ , minimum:  $-5.2^\circ$ ) for the mean value. The SDs of pelvic rotation angles  
179 among trials within each participant were  $1.3 \pm 0.5^\circ$  at peak knee flexion and  $1.1 \pm 0.5^\circ$  for  
180 the mean value. The LSI of the knee extensor moment was predicted by the pelvic rotation  
181 angle at peak knee flexion ( $R^2 = .376, p = .001$ ) (Figure 3a) but not by the LSI of the AP-  
182 COP position (Figure 3b). Pelvic rotation toward the involved limb was associated with a  
183 smaller knee extensor moment in the involved limb relative to the uninvolved limb. The  
184 stepwise multivariate regression analysis showed that the LSI of the VGRF and the pelvic  
185 rotation angle explained 63% of the variance in the LSI of the knee extensor moment  
186 (model  $R^2 = .635, p < .001$ ) (Table 2). The LSI of the AP-COP position was not included  
187 in the multivariate model. The LSI of the mean knee extensor moment was also predicted  
188 by the mean pelvic rotation angle ( $R^2 = .242, B = -4.3, \text{intercept} = 99.6, P = .015$ ). The  
189 stepwise regression analysis showed that the LSIs of the mean VGRF and the mean pelvic  
190 rotation angle were significant predictors of the LSI of the mean knee extensor moment  
191 (model  $R^2 = .609, p < .001$ ) (Table 2).

192           The LSI of the knee-to-support moment ratio was  $100.5 \pm 17.6\%$  at peak knee flexion  
193 and  $98.6 \pm 14.6\%$  at the mean value. The pelvic rotation angle predicted the LSI of the  
194 knee-to-support moment ratio at peak knee flexion ( $R^2 = .403, p < .001$ ) (Figure 4a). Pelvic  
195 rotation toward the involved limb was associated with a smaller knee-to-support moment  
196 ratio in the involved limb relative to the uninvolved limb. The LSI of the AP-COP position

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

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

210

211

## Discussion

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

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

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

247 small interlimb differences may be difficult. The assessment of pelvic rotation may be useful  
248 to predict the interlimb asymmetry in the knee extensor moment and knee-to-support moment  
249 ratio in a clinical setting.

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

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

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

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

283 A double-leg squat is a basic exercise that is commonly used for quadriceps strength  
284 training in rehabilitation after ACLR.<sup>1</sup> Co-contraction of the quadriceps with the hamstrings  
285 results in minimal or no ACL tensile force during a squatting exercise.<sup>31</sup> Therefore, a smaller  
286 knee extensor moment during a squatting exercise has an advantage in terms of protecting graft  
287 healing, especially in the early postoperative phase. However, knee extensor moment deficits  
288 during double-leg squatting are observed not only in the early postoperative phase but also  
289 more than one year after surgery.<sup>3,7</sup> The effect of squatting exercises on strengthening  
290 quadriceps may be limited by compensatory mechanisms, and these altered motor controls may  
291 prevent the recovery of quadriceps muscle strength.<sup>3,6,7,32</sup> Deficits in quadriceps strength are  
292 problematic not only in the early postoperative phase but also two years or more after surgery.<sup>10</sup>  
293 An assessment of and feedback on the pelvic rotation during squatting may be useful for  
294 modifying the interlimb asymmetry in knee extensor moment and its contribution during  
295 double-leg squatting. Trunk and pelvic control have been areas of focus in ACL injury and

296 reinjury prevention.<sup>33-35</sup> Jump-landing training with verbal instructions reduced the lateral  
297 trunk lean and knee abduction moment during single-leg landing.<sup>36</sup> Therefore, pelvic rotation  
298 might also be improved with movement training using verbal instructions. However, the  
299 assessment of small pelvic rotation angles may require three-dimensional motion analysis.  
300 Further studies are needed to clarify clinically valid assessments and the effect of feedback  
301 training to maintain neutral pelvic rotation during double-leg squatting on the knee extensor  
302 moment and its contribution.

303         The present findings should be generalized with caution. First, the results from the early  
304 postoperative period may differ from those of the present study due to the use of different  
305 compensatory strategies. Further studies examining patients in the early postoperative period,  
306 as well as the effect of interventions to modify pelvic rotation, are needed. Second, the present  
307 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  
309 study because one foot is not fixed during single-leg squatting. Moreover, further research is  
310 needed to determine if the present findings can be applied to more dynamic tasks such as  
311 double-leg landing.

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

316         In conclusion, pelvic rotation toward the involved limb was associated with a smaller  
317 knee extensor moment and knee-to-support moment ratio in the involved limb than in the  
318 uninvolved limb during double-leg squatting after ACLR. The pelvic rotation angle explained  
319 38% of the variance in the LSI of the knee extensor moment and 64% when combined with the  
320 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

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450

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

456

457

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

	<i>B</i> (95%CI)	$\beta$	<i>p</i>
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

460 LSI: limb symmetry index

461 VGRF: vertical ground reaction force

462

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

	<i>B</i> (95%CI)	$\beta$	<i>p</i>
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

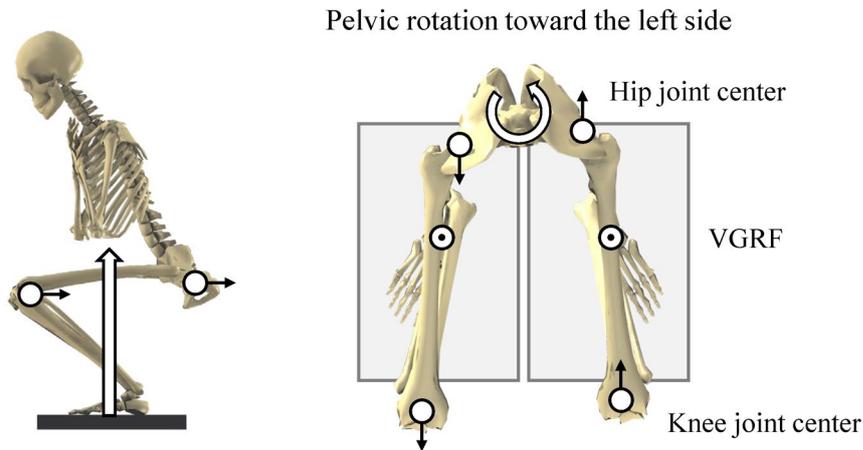
465 LSI: limb symmetry index

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

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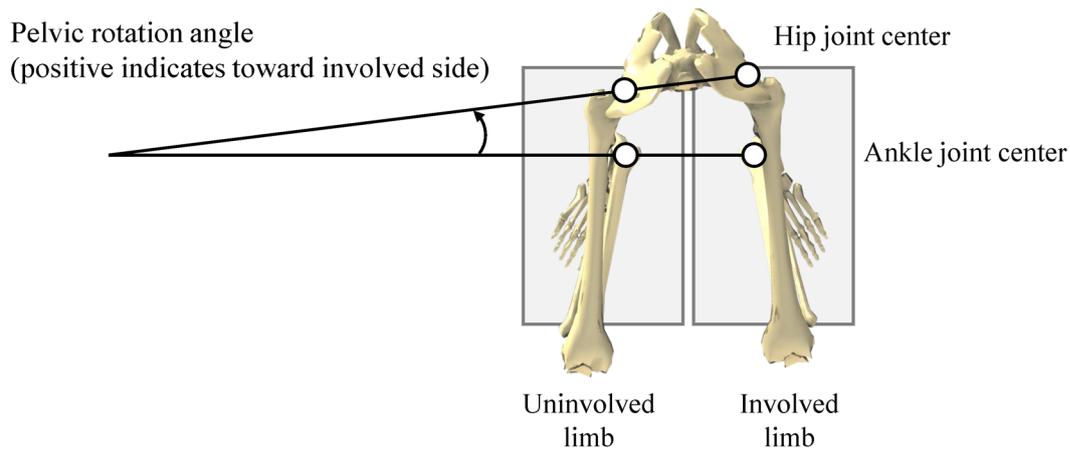
469 **Figure Captions**



470

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

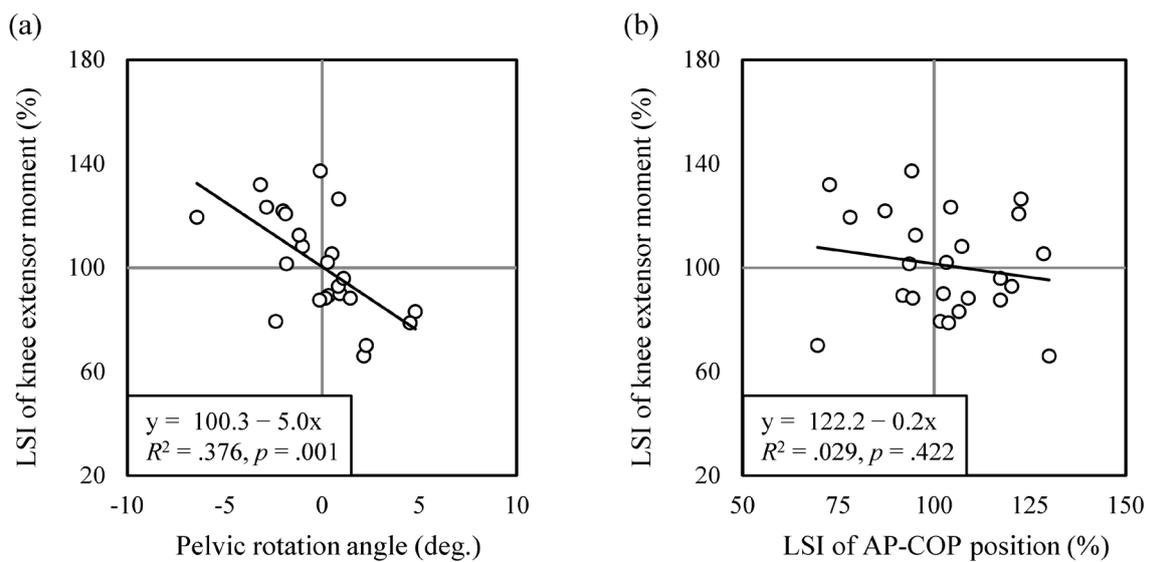
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481 **Figure 2** Pelvic rotation angle in the horizontal plane.

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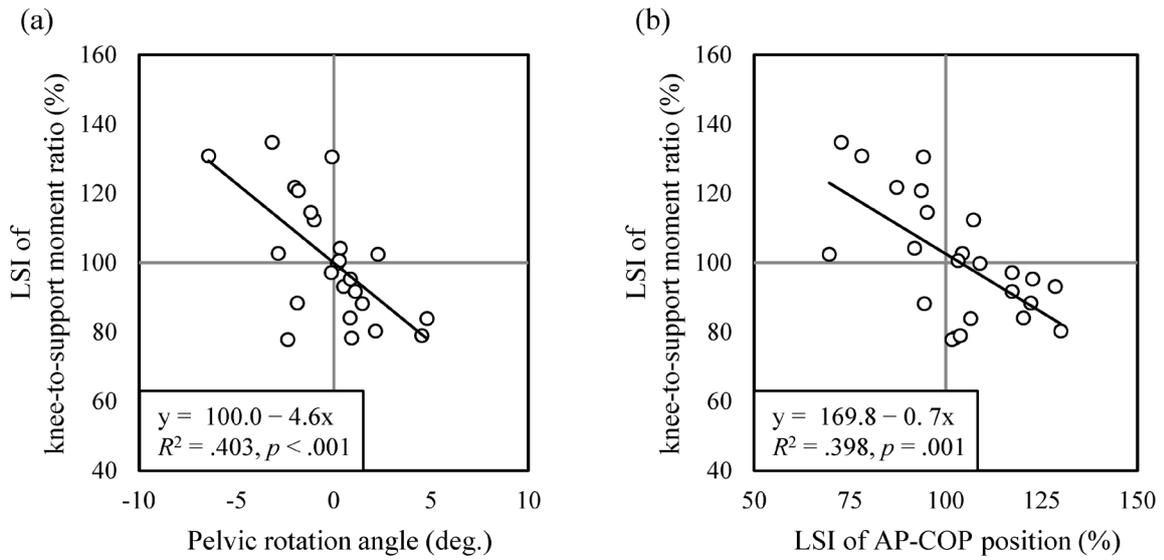


483

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

488

489



490

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