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# **Larger hip external rotation motion is associated with larger knee abduction and internal rotation motions during a drop vertical jump**

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1 **Larger hip external rotation motion is associated with larger knee**  
2 **abduction and internal rotation motions during a drop vertical jump**

3

4 **Abstract**

5 Associations among hip motions, knee abduction and internal rotation motion during a drop  
6 vertical jump (DVJ), which increases the risk of anterior cruciate ligament (ACL) injury,  
7 remain unclear. The purpose of this study was to examine associations among knee abduction,  
8 internal rotation and hip joint motions during a DVJ. Fifty-seven young female participants  
9 performed a DVJ from a 30-cm height. Hip and knee kinematics and kinetics were analysed  
10 using a three-dimensional motion analysis system and force plates. Multiple regression analysis  
11 showed that peak knee abduction angle was negatively associated with knee internal rotation  
12 and hip internal rotation excursions from initial contact (IC) to peak knee flexion, and  
13 positively associated with peak knee abduction moment ( $R^2 = 0.465$ ,  $P < 0.001$ ). Peak knee  
14 internal rotation angle was negatively associated with the hip flexion excursion from IC to peak  
15 knee flexion and peak hip adduction moment ( $R^2 = 0.194$ ,  $P = 0.001$ ). In addition, hip internal  
16 rotation excursion was negatively associated with knee abduction and internal rotation  
17 excursion from IC to 50 ms after IC. To avoid a large knee abduction and internal rotation  
18 motion during jump-landing training, it might be beneficial to provide landing instructions to  
19 avoid a large hip external rotation motion.

20

21 **Keywords:** anterior cruciate ligament (ACL); prevention; knee valgus; hip kinematics; landing

## 22 **Introduction**

23 Anterior cruciate ligament (ACL) injuries are severe sports injuries. Individuals  
24 cannot return to sports for more than 6 months after ACL reconstruction (Barber-Westin &  
25 Noyes, 2011). Furthermore, only two-thirds of athletes who underwent ACL reconstruction  
26 returned to their preinjury level of sports after surgery, and one-fifth of athletes suffered a  
27 second ACL injury after returning to sports (Ardern et al., 2014; Wiggins et al., 2016). Female  
28 athletes are more likely to sustain primary and secondary ACL injuries than male athletes (Agel  
29 et al., 2016; Paterno et al., 2017). Although some prevention programmes targeting female  
30 athletes have shown preventive effects (LaBella et al., 2011; Omi et al., 2018; Waldén et al.,  
31 2012), the overall number of ACL injuries among female athletes has not decreased (Agel et  
32 al., 2016). Therefore, prevention programmes and rehabilitation after ACL reconstruction for  
33 female athletes should be improved to reduce the risk of ACL injury in female athletes.

34 Most ACL injuries occur during noncontact deceleration, and jump landing is one of  
35 the most frequent situations leading to injury (Shimokochi & Shultz, 2008). In cadaveric  
36 landing simulations, high external knee abduction moments induced high ACL strains (Bates  
37 et al., 2019; Kiapour et al., 2016; Navacchia et al., 2019; Ueno, Navacchia, Bates, et al., 2020).  
38 A large knee abduction moment is a key mechanism of ACL injuries occurring during simulated  
39 landing (Navacchia et al., 2019; Ueno, Navacchia, Bates, et al., 2020). A previously proposed  
40 ACL injury mechanism is compression on the lateral compartment of the knee with knee  
41 abduction due to a large knee abduction moment, inducing anterior tibial translation and knee  
42 internal rotation due to the posterior slope of the tibia (Koga et al., 2010; Matsumoto, 1990;  
43 Navacchia et al., 2019; Ueno, Navacchia, Bates, et al., 2020). In fact, in noncontact ACL  
44 injuries, rapid knee abduction motion and knee internal rotation with relatively low knee  
45 flexion angle occurred immediately after initial contact (IC) with the ground (Koga et al., 2010).  
46 In addition, the peak knee abduction angle and knee abduction excursion during the first

47 landing in a drop vertical jump predicted primary and secondary ACL injuries in female athletes  
48 (Hewett et al., 2005; Paterno et al., 2010). A small knee flexion angle during a drop vertical  
49 jump was also a risk factor for ACL injury (Hewett et al., 2005; Leppänen et al., 2017).  
50 Therefore, a large knee abduction and internal rotation motion and a small knee flexion angle,  
51 as well as a large knee abduction and knee internal rotation moment, should be avoided to  
52 reduce the risk of ACL injury (Bates et al., 2019; Hewett et al., 2005; Kiapour et al., 2016;  
53 Koga et al., 2010; Leppänen et al., 2017; Navacchia et al., 2019; Paterno et al., 2010; Ueno,  
54 Navacchia, Bates, et al., 2020).

55 Previous researchers have suggested that hip and ankle motions during landing are  
56 important for reducing the risk of ACL injury because knee kinematics are affected by adjacent  
57 joints due to the kinematic chain (Hewett et al., 2005; Hogg et al., 2019; Howard et al., 2011;  
58 Ishida et al., 2015; Malloy et al., 2015, 2016; Nguyen et al., 2015; Paterno et al., 2010; Ueno,  
59 Navacchia, DiCesare, et al., 2020). Recent studies have shown that limited hip motions are  
60 indicated as risk factors for ACL injuries (Beaulieu et al., 2014; Bedi et al., 2016; Koga et al.,  
61 2018). In previous *in vitro* studies, models with restricted femoral internal rotation  
62 demonstrated larger ACL strain during simulated landing than models without restricted femur  
63 motion (Beaulieu et al., 2014; Bedi et al., 2016). Furthermore, the restriction of femoral internal  
64 rotation increased the magnitude of anterior tibial translation during simulated landing  
65 (Beaulieu et al., 2015). Moreover, a video analysis showed that the hip internal rotation angle,  
66 as well as the hip flexion and adduction angles, did not change during the early landing phase  
67 of jumps leading to ACL injuries (Koga et al., 2018). These studies indicated that smaller hip  
68 motions during landing might increase the risk of ACL injuries (Beaulieu et al., 2014, 2015;  
69 Bedi et al., 2016; Koga et al., 2018). However, the application of these *in vitro* findings may  
70 be limited because hip internal rotation was restricted by a hard stop, such as femoroacetabular  
71 impingement, in these *in vitro* studies (Beaulieu et al., 2014, 2015; Bedi et al., 2016). During

72 *in vivo* landing, the peak knee abduction angle was associated with the peak hip adduction  
73 angle but not the peak hip internal rotation angle (Hogg et al., 2019). On the other hand, another  
74 recent study has shown that the knee abduction and internal rotation angle was increased with  
75 ipsilateral trunk rotation to the knee during a double leg landing, and the authors suggested that  
76 femur external rotation is a possible mechanism underlying these findings (Critchley et al.,  
77 2020). The relationships between hip and knee joint motions during *in vivo* landing remains  
78 uncertain. In addition, which knee and hip joint motions and moments have the largest effect  
79 on the peak knee joint angles and excursions including abduction, internal rotation and flexion,  
80 it is unknown. Understanding the associations among knee and hip joint motions and external  
81 joint moment during a drop vertical jump, could help improve jump-landing training and  
82 optimise hip joint motions, thereby reducing the peak knee abduction and internal rotation  
83 angle and increasing the peak knee flexion angle.

84         The purpose of the present study was to examine the association of the peak knee joint  
85 angles (knee abduction, internal rotation and flexion) with hip joint motions and the external  
86 moment of the knee and hip joints during the first landing in a drop vertical jump. In addition,  
87 the associations of knee joint angle excursions (knee abduction, internal rotation and flexion)  
88 with hip flexion, adduction and internal rotation excursions were examined to identify the  
89 kinematic relationships. The hypotheses were that a larger peak angle and excursion for knee  
90 abduction and internal rotation and a smaller peak angle and excursion for knee flexion are  
91 associated with smaller hip internal rotation excursion or larger hip external rotation, as well  
92 as smaller hip adduction and flexion excursions.

93

## 94 **Methods**

### 95 *Participants*

96 Based on a previous study (Hogg et al., 2019), a medium effect size was estimated for an

97 independent variable. To achieve a significance level ( $\alpha$ ), statistical power ( $1 - \beta$ ) and effect  
98 size ( $f^2$ ) of 0.05, 0.8 and 0.15 in the regression model, respectively, 55 participants were needed.  
99 Considering the possibility of data deficiency, 57 healthy female participants (mean  $\pm$  SD: age  
100  $21.1 \pm 1.3$  years, height  $160.6 \pm 6.5$  cm, mass  $52.9 \pm 6.9$  kg) participated in this study.  
101 Individuals were excluded if they reported a history of musculoskeletal injuries or disorders  
102 within the last 6 months, severe injuries of the lower extremities or trunk, knee injuries, or  
103 participation in an ACL injury prevention programme. All participants had experience with  
104 regular sports, such as basketball, handball or soccer. The right leg was tested and analysed  
105 because the dominant side of all participants was the right side. The dominant leg was defined  
106 as the side preferable for kicking a ball. Prior to participation, the participants were provided  
107 information regarding this study and were required to sign informed consent forms. The present  
108 study was approved by the review board of the Faculty of Health Sciences, Hokkaido  
109 University (11-55).

110

### 111 *Procedures and data collection*

112 The participants warmed up on a stationary bicycle for 5 min and then performed a standardised  
113 static standing trial, followed by landing trials. A drop vertical jump task was used to evaluate  
114 the landing kinematics. The participants were instructed to drop from a 30-cm-high box and  
115 then land on two force plates (Type 9286, Kistler AG, Winterthur, Switzerland) with one foot  
116 on each plate and perform a maximum vertical jump immediately thereafter. Practice trials  
117 were permitted to allow the participants to become familiar with the landing task. Three  
118 successful trials of drop vertical jumps were collected.

119 Synchronised marker coordinates and force data were recorded using EVaRT 4.4  
120 (Motion Analysis Corp., Santa Rosa, CA, USA) with six digital cameras (Hawk cameras,  
121 Motion Analysis Corp.) and the force plates. The two force plates were positioned 5.5 cm apart

122 and 10 cm in front of the box to land on a different force plate with each foot (Ishida et al.,  
123 2015; Nguyen et al., 2015). The sampling rate was 200 Hz for the marker coordinate data and  
124 1,000 Hz for the force plate data. In total, 39 retroreflective markers were placed on the bony  
125 landmarks of the pelvis and lower extremities (the sacrum, right iliac crest and medial knee,  
126 both shoulders, anterosuperior iliac spines (ASIS), greater trochanters, lateral knees, medial  
127 and lateral ankles, heels, and second and fifth metatarsal heads), and 10 and 6 cluster markers  
128 were placed on the right thigh and shank, respectively.

129

### 130 *Data processing and reduction*

131 The first landing in the drop vertical jump task was analysed because the knee abduction angle  
132 and moment during the first landing have been shown to predict ACL injuries (Hewett et al.,  
133 2005; Paterno et al., 2010). In addition, the first landing yielded larger knee abduction motion  
134 and moment than the second landing and a drop landing without a subsequent jump (Bates et  
135 al., 2013; Ishida et al., 2018). Three-dimensional knee and hip kinematics were estimated using  
136 a rigid-body skeletal model with a joint coordinate system using SIMM 6.0.2 software  
137 (MusculoGraphics Inc., Santa Rosa, CA, USA) (Delp et al., 1990). The marker trajectory data  
138 were low-pass filtered using a fourth order Butterworth filter with a 12-Hz cutoff frequency.  
139 The ground reaction force data were low-pass filtered using a generalised cross validation  
140 spline with a 25-Hz cutoff frequency. The joint angles were calculated using the Cardan  
141 sequence (flexion/extension, abduction/adduction, and then internal/external rotation), and  
142 those during the static standing trial were set to zero and served as references for the drop  
143 vertical jump trials. The positive angles indicate knee flexion, abduction and internal rotation;  
144 and hip flexion, adduction and internal rotation. The analysed landing phase was defined as the  
145 phase from the initial contact (IC) to the peak knee flexion. IC was defined as when the vertical  
146 ground reaction force first exceeded 10 N (Ford et al., 2007). The peak knee flexion, abduction

147 and internal rotation angles during the landing phase were derived. Angular excursions of the  
148 knee and hip joints were calculated from IC to 50 ms after IC. This time range was chosen for  
149 the analysis since it is the time range during which ACL injuries have been shown to occur  
150 (Koga et al., 2010; Ueno, Navacchia, Bates, et al., 2020). In addition, angular excursions of the  
151 knee and hip joints from IC to peak knee flexion were calculated to examine the association  
152 between the peak knee joint angles (flexion, abduction and internal rotation) and knee and hip  
153 joint motion during the landing phase. The external moments at the joints were also estimated  
154 using inverse dynamics with SIMM software. The segment inertial parameters were selected  
155 based on a previous report (de Leva, 1996). The peak moments of the knee and hip joints were  
156 derived and normalised to the body mass and height (Nm/kg/m). The positive moments indicate  
157 knee flexion, abduction and internal rotation; and hip flexion, adduction and internal rotation.

158

### 159 *Statistical analysis*

160 A stepwise multiple regression analysis was conducted to determine which kinetic and  
161 kinematic variables of the hip and knee joints predict the peak knee flexion, abduction and  
162 internal rotation angles and the excursion of knee flexion, abduction and internal rotation  
163 excursions from IC to 50 ms after IC. The independent variables were the excursions of the  
164 knee and hip joints from IC to peak knee flexion or 50 ms after IC, the peak external moments  
165 of the knee and hip joints, and the peak vertical ground reaction force. The criterion for a  
166 dependent variable to be included was  $P < 0.05$ , and the criterion to exclude a dependent  
167 variable was  $P > 0.10$ . The statistical analyses were performed using the IBM SPSS Statistics  
168 22 software program (IBM Corporation, Armonk, NY, USA). and the level of significance was  
169 set to  $P < 0.05$ .

170

### 171 **Results**

172 The knee flexion angle increased from  $23.9 \pm 6.7^\circ$  at IC to  $51.9 \pm 5.8^\circ$  at 50 ms after IC and  
173  $83.0 \pm 10.9^\circ$  at the peak (Fig. 1A). The hip flexion, hip adduction and knee abduction angles  
174 showed an increasing tendency from IC to the peak knee flexion (Fig. 1B, D and E). In contrast,  
175 the knee internal rotation angle reached its peak at  $50.6 \pm 16.7$  ms after IC, and then the knee  
176 rotated externally (Fig. 1C). Regarding the hip rotation motion, the average curve displayed  
177 small external rotation motion because two motion patterns were observed among the  
178 participants (Fig. 1F). Twenty-five participants demonstrated hip internal rotation motion  
179 (increased internal rotation or decreased external rotation), while the other 32 participants  
180 demonstrated hip external rotation motion (Fig. 2).

181 The multiple regression analysis revealed that the knee internal rotation and hip  
182 internal rotation from IC to peak knee flexion and the peak knee abduction moment predicted  
183 the peak knee abduction angle ( $R^2 = 0.465$ ,  $P < 0.001$ ) (Table 1). Negative associations were  
184 found with the knee internal rotation excursion and hip internal rotation excursion (Fig. 3A),  
185 while a positive association was found with the peak knee abduction moment. From IC to 50  
186 ms after IC, the hip internal rotation excursion, knee internal rotation excursion and the peak  
187 knee abduction moment predicted the knee abduction excursion ( $R^2 = 0.292$ ,  $P < 0.001$ ) (Table  
188 2). The peak knee abduction moment was positively associated, while the hip internal rotation  
189 excursion (Fig. 4A) and knee internal rotation excursion were negatively associated with the  
190 knee abduction excursion from IC to 50 ms after IC.

191 The peak knee internal rotation angle was predicted by the hip flexion excursion from  
192 IC to peak knee flexion and the peak hip adduction moment ( $R^2 = 0.194$ ,  $P = 0.003$ ) (Table 1).  
193 Negative associations were found with the hip flexion excursion (Fig. 3B) and peak hip  
194 adduction moment. The knee internal rotation excursion from IC to 50 ms after IC was  
195 predicted by the hip internal rotation and knee abduction excursions from IC to 50 ms after IC  
196 and the peak knee flexion moment ( $R^2 = 0.302$ ,  $P < 0.001$ ) (Table 2). Negative associations

197 were found with the hip internal rotation excursion (Fig. 4B) and knee abduction excursion.

198           The hip flexion excursion from IC to peak knee flexion and the peak vertical ground  
199 reaction force were included in the regression model of the peak knee flexion angle ( $R^2 = 0.636$ ,  
200  $P < 0.001$ ) (Table 1). The hip flexion excursion was positively associated with the knee flexion  
201 excursion, while the peak vertical ground reaction force was negatively associated with the  
202 knee flexion excursion. The knee flexion excursion from IC to 50 ms after IC was explained  
203 by the hip flexion excursion from IC to 50 ms after IC and the peak knee abduction moment  
204 ( $R^2 = 0.641$ ,  $P < 0.001$ ) (Table 2).

205

## 206 **Discussion and implications**

207 The purpose of the present study was to identify the associations of the peak knee joint angles  
208 and excursions (knee abduction, internal rotation and flexion) with hip joint motions and  
209 external moments of the knee and hip joints during the first landing in a drop vertical jump task.

210 A main finding of the present study is that a smaller hip internal or a larger hip external rotation  
211 excursion from IC to peak knee flexion was associated with a larger peak knee abduction angle.

212 A smaller internal or a larger external hip rotation excursion was also associated with a larger  
213 knee abduction and internal rotation excursion during the 50 ms after IC. In addition, a smaller  
214 hip flexion excursion was associated with a smaller peak knee flexion and a larger peak knee  
215 internal rotation angle. These findings partially support the *a priori* hypothesis that a smaller  
216 hip internal rotation excursion or a larger hip external rotation, as well as smaller hip adduction  
217 and flexion excursions are associated with larger peak angles and excursions for knee abduction  
218 and internal rotation and a smaller peak angle and excursion for knee flexion.

219           The present study showed that hip internal rotation excursion was a predictor in the  
220 regression models that predicted the peak knee abduction angle, the knee abduction excursion,  
221 and the knee internal rotation excursion from IC to 50 ms after IC. A smaller internal or a larger

222 external hip rotation motion was associated with a larger peak knee abduction angle and a larger  
223 knee abduction excursion from IC to 50 ms after IC. Even among the participants with larger  
224 knee abduction moments, the peak knee abduction angle and the knee abduction excursion  
225 tended to be smaller when the participants showed hip internal rotation patterns or smaller hip  
226 external rotation excursions. Previous studies reported that a larger femoral anteversion was  
227 associated with a larger knee abduction excursion during single-leg and double-leg landings  
228 (Howard et al., 2011; Nguyen et al., 2015). Although these studies suggested the possibility  
229 that a large hip internal rotation motion could be associated with a large knee abduction during  
230 single-leg and double-leg landings, the present study showed that the kinematic relationship  
231 between knee abduction and hip rotation motion during a double-leg landing was the opposite.  
232 On the other hand, another study showed that a large knee abduction angle was associated with  
233 a large hip adduction angle but not a hip internal rotation angle during a single-leg landing  
234 (Hogg et al., 2019). Therefore, the kinematic relationship between the knee and hip may differ  
235 between double-leg and single-leg landings. When the external knee abduction moment is  
236 applied, knee abduction motion accompanied by hip internal rotation might be the natural  
237 kinematic relationship, which is known as the dynamic valgus alignment of the lower extremity  
238 (Hewett et al., 2010; Olson et al., 2011). Although hip internal rotation motion can be associated  
239 with lower extremity dynamic valgus alignment (Hewett et al., 2010; Olson et al., 2011), the  
240 results of the present study showed that a large hip internal rotation was not associated with a  
241 large knee abduction during a landing. When the medial tilt of the tibia occurs with the hip  
242 internal rotation at the knee flexed position with the foot in contact with the ground, the motion  
243 directions of both the tibia and femur could face the same direction, and knee abduction might  
244 be diminished (Fig. 5A). In contrast, hip external rotation motion would cause the femur to  
245 face the opposite direction to the medial tilt of the tibia and could increase knee abduction  
246 motion (Fig. 5B). Ipsilateral trunk rotation motion to the knee, which could be associated with

247 femur external rotation, increased the knee abduction angle during a double leg landing  
248 (Critchley et al., 2020), which is consistent with the present findings. However, the lack of a  
249 cause-effect relationship is acknowledged in the present study. Additional studies are necessary  
250 to examine the effect of instruction to avoid a large hip external rotation motion on knee  
251 abduction motion during a double-leg landing.

252         A smaller internal or larger external hip rotation excursion was also associated with a  
253 larger knee internal excursion during the 50 ms after IC. Previous *in vitro* studies have shown  
254 that a restriction of the hip internal rotation increases the ACL strain compared to no restrictions  
255 due to increases in anterior tibial translation and knee internal rotation in a simulated landing  
256 task (Beaulieu et al., 2014, 2015; Bedi et al., 2016). Although hip internal rotation was  
257 restricted by a hard stop, such as bony impingement, in these *in vitro* studies, the present *in*  
258 *vivo* study supports the previous hypothesis that hip internal rotation can decrease knee internal  
259 rotation during the early landing phase (Beaulieu et al., 2014; Bedi et al., 2016). In addition,  
260 ipsilateral trunk rotation, which could be associated with the femur external rotation to the  
261 pelvis, increased the knee internal rotation angle during a double-leg landing (Critchley et al.,  
262 2020). The present findings also suggest the possibility that hip external rotation motion might  
263 increase knee internal rotation during a landing, although the cause-effect relationship between  
264 hip rotation and knee rotation motion is uncertain based on the present study. Further studies  
265 are necessary to reveal the mechanism underlying these kinematic relationships.

266         A smaller hip flexion excursion was associated with a larger peak knee internal  
267 rotation and a smaller peak knee flexion angle and knee flexion excursion from IC to 50 ms  
268 after IC. These associations seem to be similar to previous video analysis studies that showed  
269 a rapid knee internal rotation immediately after landing in cases of ACL injury (Koga et al.,  
270 2010), while the hip flexion angle did not change (Koga et al., 2018). A smaller total of hip  
271 flexion and knee flexion during landing was associated with a larger knee abduction angle and

272 moment during a drop vertical jump (Pollard et al., 2010). A landing pattern that relies on  
273 passive restraints to decelerate the body centre of mass, instead of knee and hip flexion, is  
274 referred to as the ‘ligament dominance’ strategy, which is considered indicative of poor  
275 neuromuscular control associated with ACL injury (Pollard et al., 2010). Although the  
276 mechanism underlying the relationship between the peak knee internal rotation angle and hip  
277 flexion excursion was not found in this study, the present findings could indicate a ‘ligament  
278 dominance’ strategy in female participants. A small peak knee flexion angle during a drop  
279 vertical jump was also reported to be a risk factor of ACL injury (Hewett et al., 2005; Leppänen  
280 et al., 2017). Small knee flexion angles are associated with high ACL strain (Markolf et al.,  
281 1995). Therefore, the hip flexion motion would be important in relation to knee flexion motion.

282         The regression analysis showed that the hip internal rotation excursion was negatively  
283 associated with the peak knee abduction angle, the knee abduction excursion, and knee internal  
284 rotation excursion from IC to 50 ms. Hence, the regression analysis also showed that the knee  
285 internal rotation excursion from IC to peak knee flexion was negatively associated with the  
286 peak knee abduction angle and that the knee internal rotation excursion was negatively  
287 associated with the knee abduction excursion from IC to 50 ms after IC. These results initially  
288 seem contradictory but are not surprising because the regression model includes adjustments  
289 for other variables, such as hip internal rotation excursion. Among healthy participants in the  
290 quasi-static lunge position, dynamic knee valgus alignment was associated with increasing  
291 knee abduction and external rotation angles (Ishida et al., 2014). The coupling of knee  
292 abduction with knee internal rotation was one of the occurring mechanisms of ACL injuries  
293 (Koga et al., 2010; Matsumoto, 1990; Navacchia et al., 2019; Ueno, Navacchia, Bates, et al.,  
294 2020). Therefore, the negative association between knee abduction and knee internal rotation  
295 observed in the present *in vivo* study could be a natural motion pattern to avoid ACL injury.

296         Concerning its application, the present study showed that hip internal rotation motion,

297 rather than external rotation, was associated with a smaller peak knee abduction angle and  
298 smaller excursion to knee abduction and internal rotation during the early landing phase in a  
299 drop vertical jump task. To reduce knee abduction and internal rotation motion in jump-landing  
300 training, it might be beneficial to provide instructions to avoid a large hip external rotation  
301 motion during a double-leg landing. However, the present study did not address the cause-  
302 effect relationship between hip internal rotation and knee abduction and internal rotation.  
303 Additional studies are needed to reveal whether landing instructions to avoid a large hip  
304 external rotation motion could reduce knee abduction and internal rotation during a double-leg  
305 landing. Although the relationship between the passive range of motion (ROM) and hip rotation  
306 motion during a landing is unclear, a sufficient ROM to allow for hip internal rotation motion  
307 would be important. Previous studies have also shown that patients with ACL tears have a  
308 significantly smaller internal rotation ROM in the hip than control participants (Bedi et al.,  
309 2016; Ellera Gomes et al., 2008; Tainaka et al., 2014). To control hip rotation motion during a  
310 landing, muscular function would also be important. The hip external rotator strength is a  
311 predictor of ACL injuries (Khayambashi et al., 2016), and hip targeted ACL injury prevention  
312 programmes decreased ACL injury risk (LaBella et al., 2011; Omi et al., 2018; Waldén et al.,  
313 2012). The eccentric contraction of the hip external rotators would be necessary for a controlled  
314 hip internal rotation motion (Malloy et al., 2016). However, this study lacked information  
315 regarding muscle strength and activation during landing. Hip internal rotators might also be  
316 important to avoid a large hip external rotation motion during landing. Therefore, future studies  
317 are needed to clarify the role of hip internal rotators and hip external rotators during a double-  
318 leg landing. Hip flexion excursion was positively associated with the peak knee flexion angle  
319 but negatively associated with the peak knee internal rotation angle in the present study.  
320 Instructions to increase hip flexion motion during a landing might induce an increase in the  
321 knee flexion motion and a decrease in the peak knee internal rotation angle. As used in previous

322 studies, instruction to emphasise hip flexion motion during landing in jump-landing training  
323 could be important to prevent ACL injury (LaBella et al., 2011; Omi et al., 2018; Pollard et al.,  
324 2010).

325         There are some limitations that should be acknowledged. First, the association  
326 between knee abduction motion and hip internal rotation motion in other tasks, such as single-  
327 leg landing and jump-cutting tasks with a change in direction, might differ from the findings  
328 reported in the present study investigating double-leg landing. The pelvis might rotate more on  
329 the transverse plane in single-leg landing than double-leg landing. In addition, the hip rotation  
330 motion would be larger during the movement of directional change after landing than during  
331 the drop vertical jump task used in the present study. Additional studies should be conducted  
332 to investigate this association in single-leg landing and jump-cutting tasks with a change in  
333 direction. Second, whether an intervention to avoid hip external rotation motion reduces the  
334 knee abduction and internal rotation angles during landing is unclear. Additional studies should  
335 be conducted to investigate the effects of jump-landing training focusing on hip rotational  
336 motions. Third, this study investigated only female participants. Therefore, the kinematic  
337 relationships observed in the present study might not apply to male participants. Finally, the  
338 effects of skin movement on frontal- and transverse-plane hip and knee joint motions should  
339 be acknowledged. Skin artefacts might have impacted the results of the present study.

340

### 341 **Conclusion**

342 The present study examined the associations of the peak knee joint angles and knee joint  
343 angular excursions with hip joint motions during a drop vertical jump. The multiple regression  
344 analysis showed that a smaller hip internal rotation or a larger hip external rotation excursion  
345 was associated with a larger peak knee abduction angle and a larger excursion to knee abduction  
346 and knee internal rotation from IC to 50 ms after IC. In addition, a smaller hip flexion excursion

347 was associated with smaller peak knee flexion and a larger peak knee internal rotation angle.  
348 Therefore, jump-landing training to avoid a large knee abduction and internal rotation motion  
349 might be beneficial for avoiding a large hip external rotation, in addition to increasing hip  
350 flexion motion during a double-leg landing.

351

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355

356 **Disclosure statement**

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358

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1 **Table 1** Multiple regression models to determine the associations of the peak knee joint angles  
 2 with hip and knee joint angle excursions and moments

	Partial correlation	$\beta$	$P$
<b>Peak knee flexion angle (°)</b>			
Hip flexion excursion (°) <sup>a</sup>	0.760	0.714	< 0.001
Peak vertical ground reaction force (Nm/kg) <sup>b</sup>	-0.362	-0.237	0.006
<b>Peak knee abduction angle (°)</b>			
Knee internal rotation excursion (°) <sup>a</sup>	-0.534	-0.488	< 0.001
Hip internal rotation excursion (°) <sup>a</sup>	-0.539	-0.475	< 0.001
Peak knee abduction moment (Nm/kg/m) <sup>c</sup>	0.286	0.221	0.035
<b>Peak knee internal rotation angle (°)</b>			
Hip flexion excursion (°) <sup>a</sup>	-0.421	-0.434	0.001
Peak hip adduction moment (Nm/kg/m) <sup>c</sup>	-0.272	-0.264	0.043

3 Model for the peak knee flexion angle:  $R^2 = 0.636$ ,  $P < 0.001$ ; Model for the peak knee  
 4 abduction angle:  $R^2 = 0.465$ ,  $P < 0.001$ ; Model for the peak internal rotation angle:  $R^2 = 0.194$ ,  
 5  $P = 0.003$

6 <sup>a</sup>excursion from initial contact (IC) to peak knee flexion

7 <sup>b</sup>normalised to body mass

8 <sup>c</sup>normalised to body mass and height

9

10 **Table 2** Multiple regression models to determine the associations of the knee joint excursions  
 11 during the 50 ms after initial contact with hip and knee joint angle excursions and moments

	Partial correlation	$\beta$	$P$
<b>Knee flexion excursion (°) <sup>a</sup></b>			
Hip flexion excursion (°) <sup>a</sup>	0.798	0.794	< 0.001
Peak knee abduction moment (Nm/kg/m) <sup>b</sup>	-0.272	-0.170	0.042
<b>Knee abduction excursion (°) <sup>a</sup></b>			
Hip internal rotation excursion (°) <sup>a</sup>	-0.452	-0.466	0.001
Peak knee abduction moment (Nm/kg/m) <sup>b</sup>	0.281	0.253	0.037
Knee internal rotation excursion (°) <sup>a</sup>	-0.276	-0.268	0.042
<b>Knee internal rotation excursion (°) <sup>a</sup></b>			
Hip internal rotation excursion (°) <sup>a</sup>	-0.544	-0.513	< 0.001
Knee abduction excursion (°) <sup>a</sup>	-0.284	-0.297	0.027
Peak knee flexion moment (Nm/kg/m) <sup>b</sup>	0.263	0.292	0.031

12 Model for the knee flexion excursion:  $R^2 = 0.641$ ,  $P < 0.001$ ; Model for the knee abduction  
 13 excursion:  $R^2 = 0.292$ ,  $P < 0.001$ ; Model for the knee rotation excursion:  $R^2 = 0.302$ ,  $P < 0.001$

14 <sup>a</sup>excursion from initial contact (IC) to 50 ms after IC

15 <sup>b</sup>normalised to body mass and height

### **Figure captions**

**Fig. 1** Average curves of the knee flexion (A), knee abduction (B), knee internal rotation (C), hip flexion (D), hip adduction (E) and hip internal rotation (F) angles. Positive values indicate knee flexion, abduction and internal rotation; and hip flexion, adduction and internal rotation. Error bars indicate  $\pm$  one standard deviation. The landing phase from initial contact to peak knee flexion was normalised to 101 data points.

**Fig. 2** The two patterns of hip rotation motion. Twenty-five participants demonstrated hip internal rotation motion (solid black line), while 32 participants demonstrated hip external rotation motion (grey dashed line). Error bars indicate  $\pm$  one standard deviation. The landing phase from initial contact to peak knee flexion was normalised to 101 data points.

**Fig. 3** The associations between the peak knee abduction angle and the hip internal rotation excursion from initial contact (IC) to peak knee flexion (A) and the association between the peak knee internal rotation angle and the hip flexion excursion from IC to peak knee flexion (B). The positive values indicate knee abduction, knee internal rotation, hip internal rotation, and hip flexion.

**Fig. 4** The associations of between knee abduction and hip internal rotation excursions (A) and between knee internal rotation and hip internal rotation excursions (B) from initial contact (IC) to 50 ms after IC. The positive values indicate knee abduction, knee internal rotation and hip internal rotation.

**Fig. 5** Schematic of the hypothesis about the association between knee abduction motion and hip rotation motion during a landing. When the medial tilt of the tibia occurs with hip internal rotation at the knee flexed position, the motion directions of both the tibia and femur would face in the same direction. Thus, the knee abduction motion might be diminished (A). When the medial tilt of tibia occurs with hip external rotation at the knee flexed position, the femur faces in the opposite direction to the medial tilt of the tibia. Thus, the knee abduction motion might be increased (B).

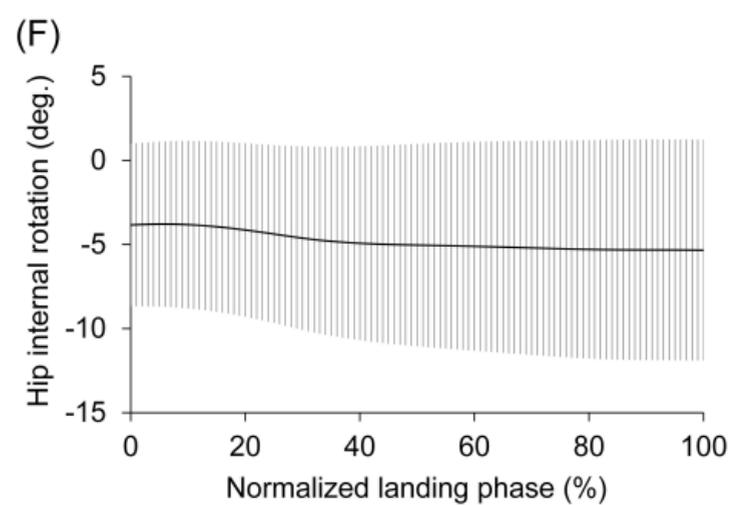
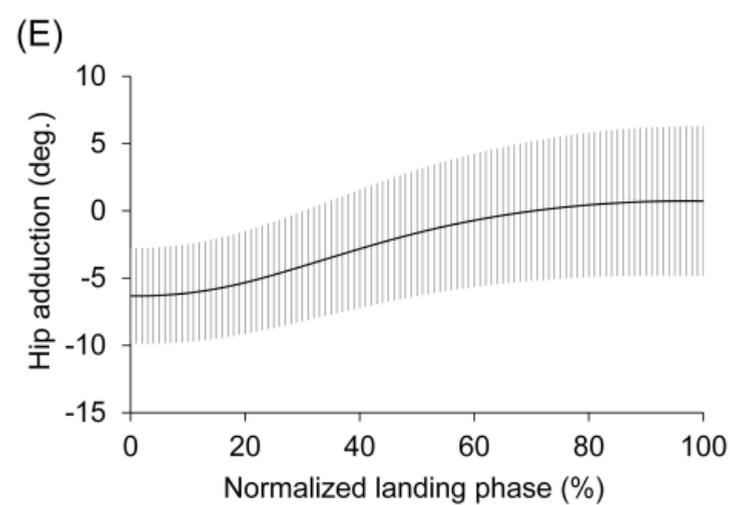
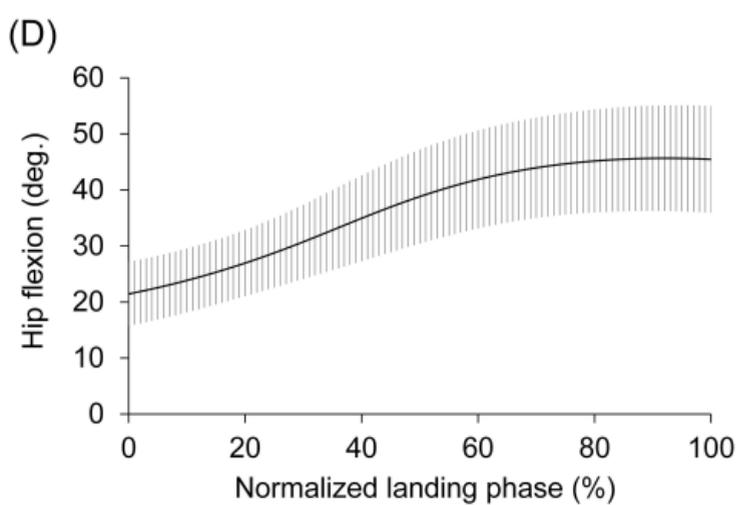
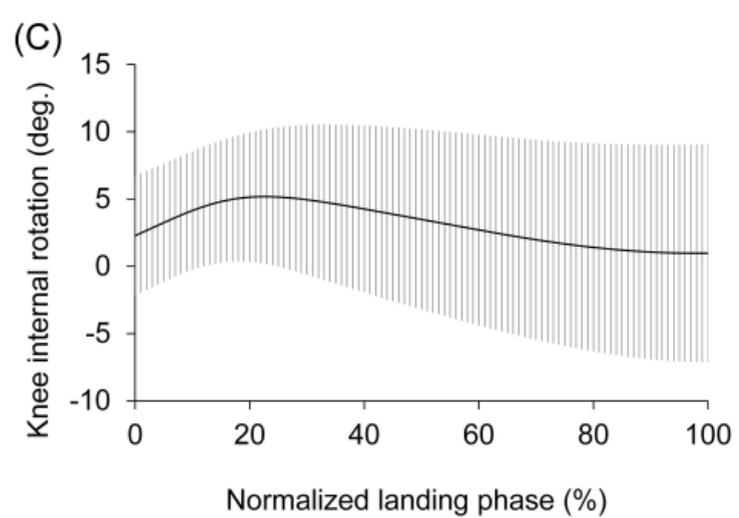
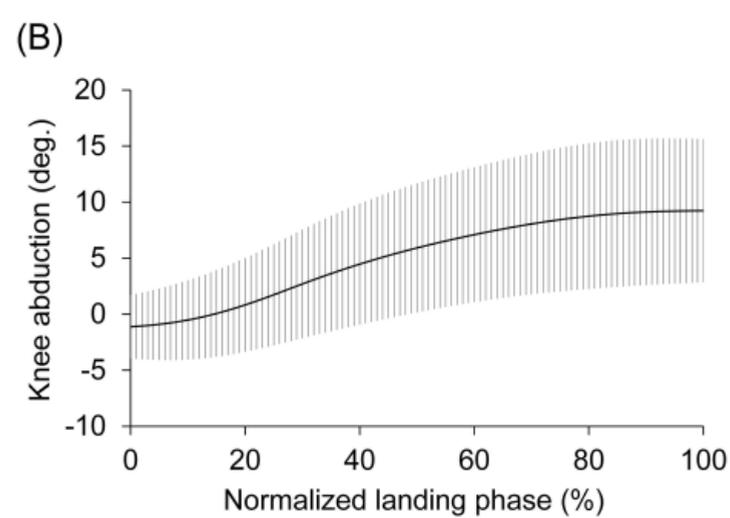
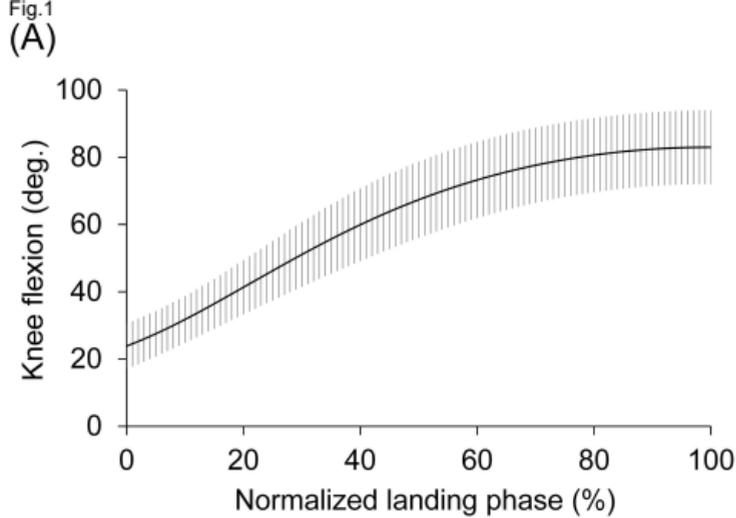


Fig.2

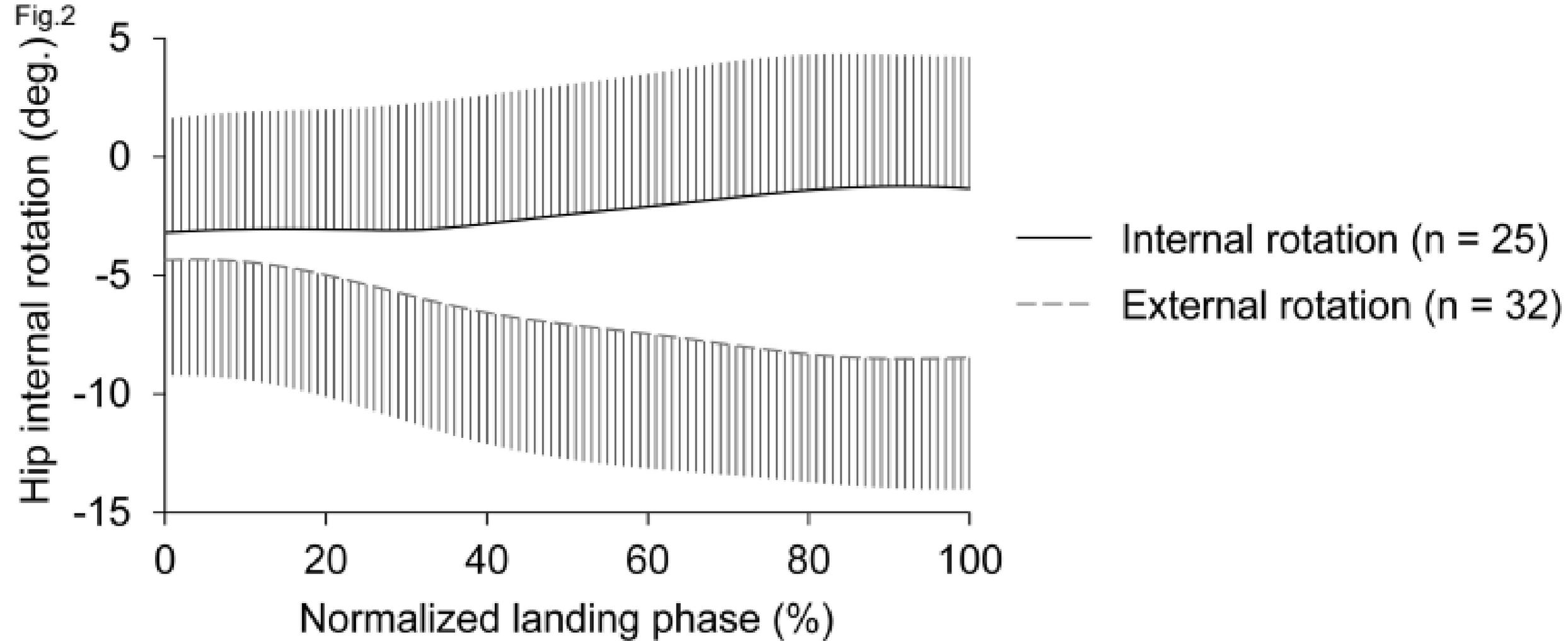
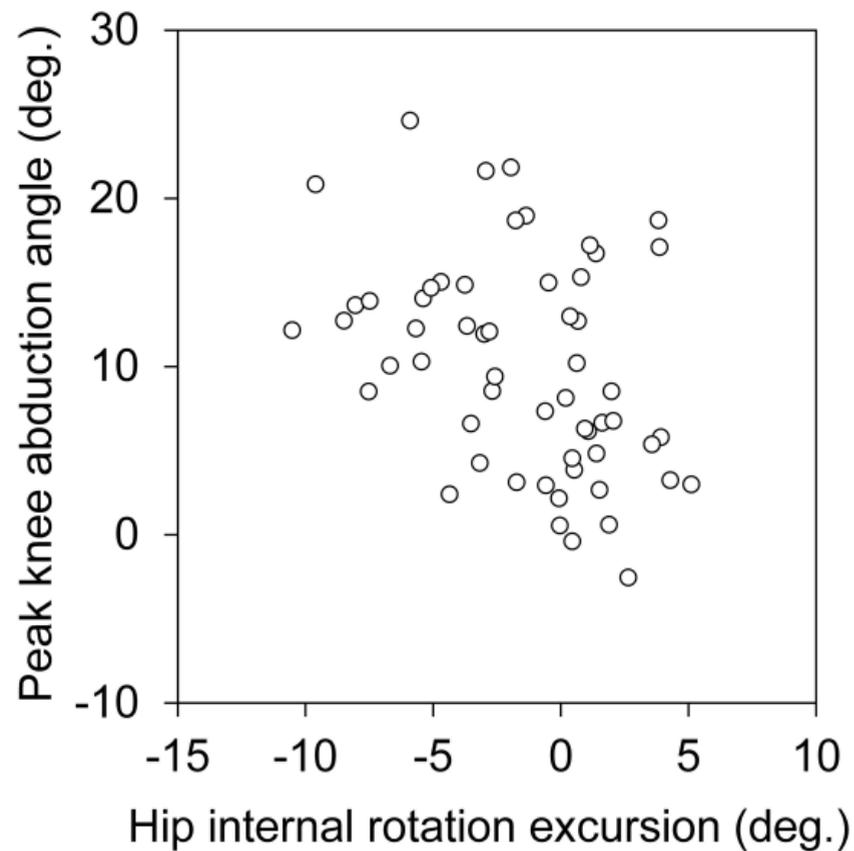


Fig.3  
(A)



(B)

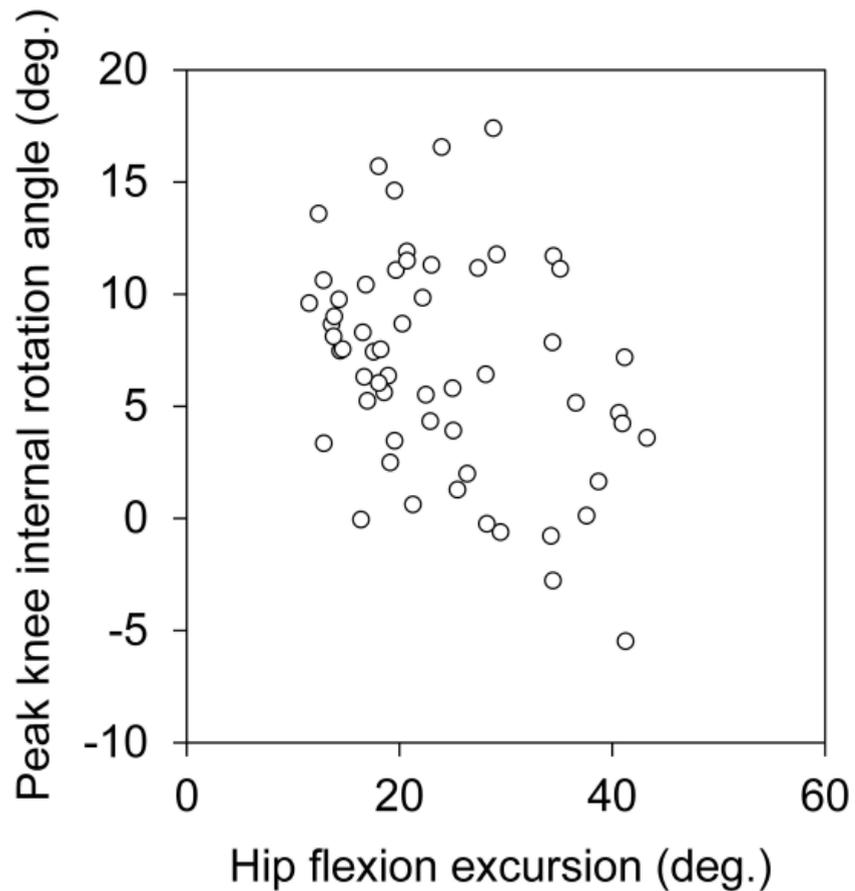
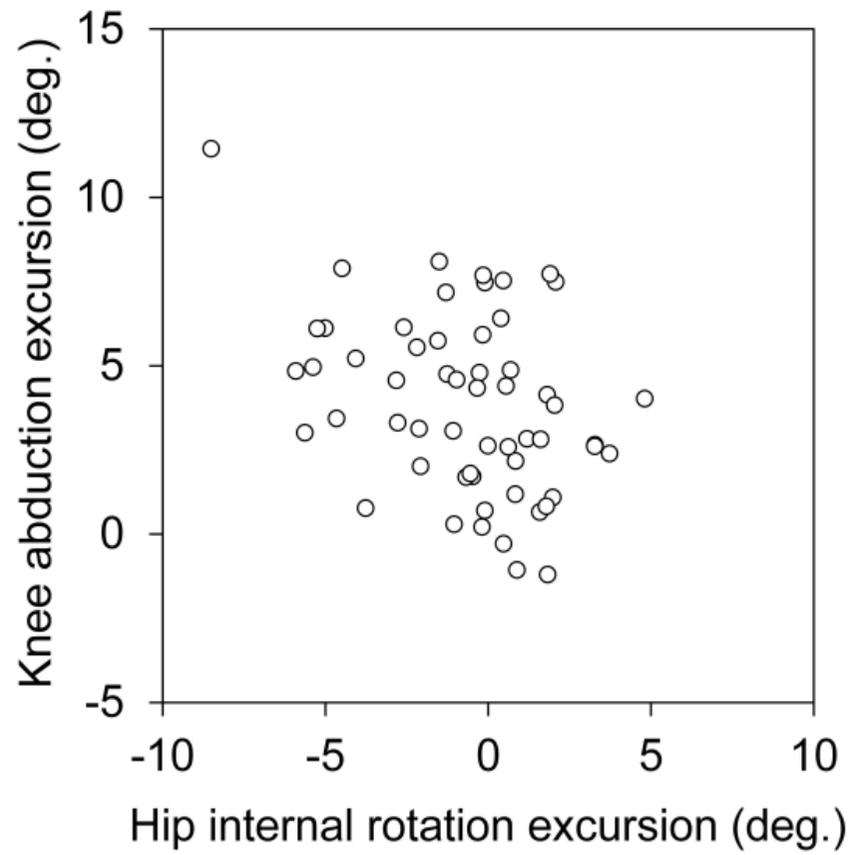


Fig.4

(A)



(B)

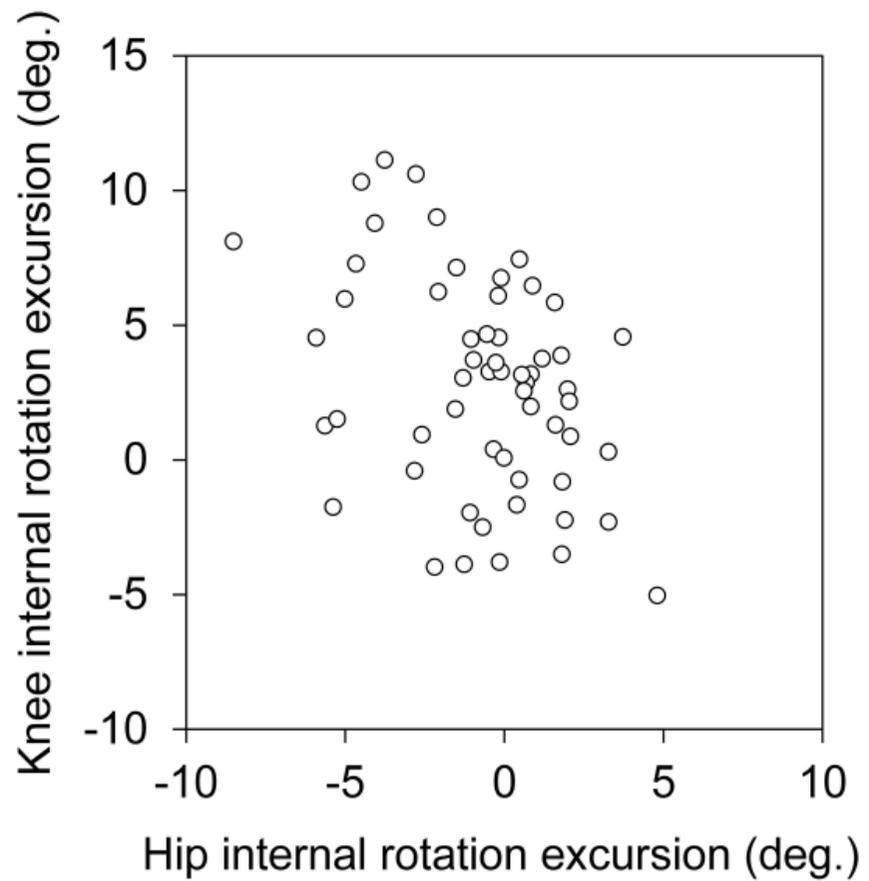


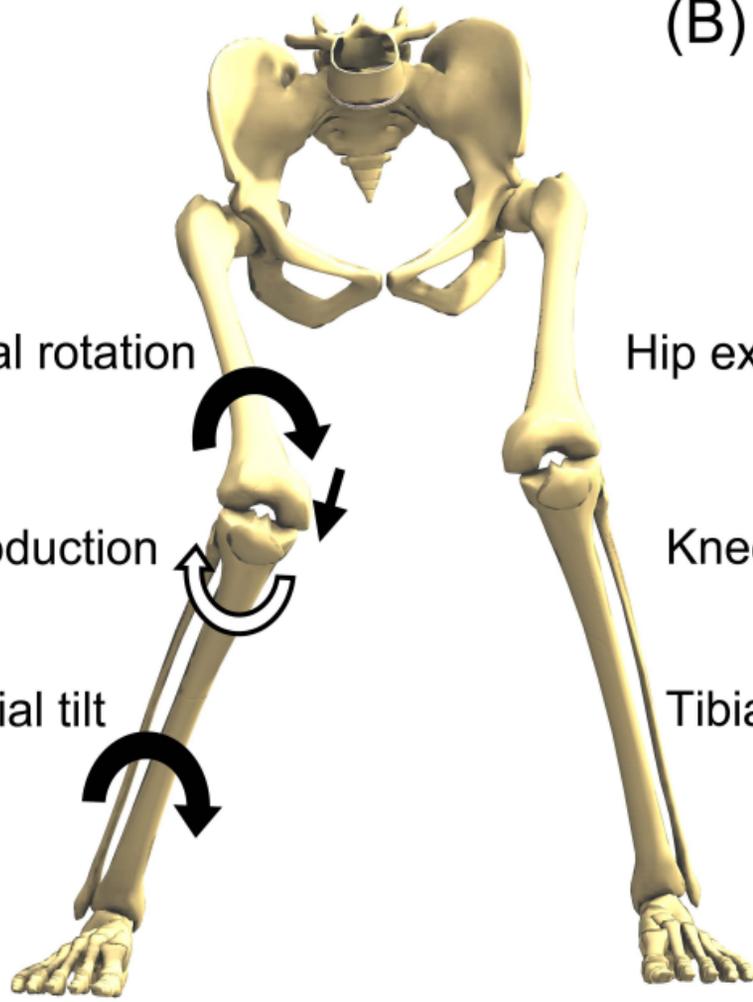
Fig.5

(A)

Hip internal rotation

Knee abduction

Tibial medial tilt



(B)

Hip external rotation

Knee abduction

Tibial medial tilt

