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# Improvements in asymmetry in knee flexion motion during landing are associated with the postoperative period and quadriceps strength after anterior cruciate ligament reconstruction

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# Declarations

No potential competing interest was reported by the authors.

1 Improvements in asymmetry in knee flexion motion during landing are associated with 2 the postoperative period and quadriceps strength after anterior cruciate ligament 3 reconstruction

4

# 5 Abstract

6 This study investigated the relationship between quadriceps strength and knee kinematics during a drop vertical jump (DVJ) at 6, 9 and 12 months after anterior cruciate ligament 7 reconstruction (ACLR) in 9 male and 22 female athletes (16.6  $\pm$  2.1 years old). Isokinetic 8 9 quadriceps strength was measured by a dynamometer (Biodex System 3). Knee flexion excursion was assessed using two-dimensional analysis. Knee flexion excursion at 6 months 10was significantly smaller in the involved limb than in the uninvolved limb independent of 11 quadriceps strength (56.7°  $\pm$  9.3°, 63.4°  $\pm$  11.4°, P < 0.001). At 9 months, only the low 12quadriceps strength group demonstrated a similar interlimb difference (57.2° $\pm$  12.3°, 63.3°  $\pm$ 131410.5°, P < 0.001). At 12 months, there was no significant interlimb difference in knee flexion excursion regardless of quadriceps strength. These findings indicate that restoration in 15symmetrical knee flexion excursion during a DVJ requires rehabilitation as well as quadriceps 1617strength.

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# 21 Introduction

The rate of a second ACL injury (i.e., graft tear or contralateral ACL tear) is 20% after return to sports (RTS) (Wiggins et al., 2016). Participation in jumping and/or cutting sports and young age were reported as risk factors for a second injury (Graziano et al., 2017; Paterno et al., 2017; Wiggins et al., 2016). Insufficient functional recovery has been suggested to be a possible cause for second ACL injuries because most injuries occur within one year after reconstruction surgery (Graziano et al., 2017; Grindem et al., 2016; Paterno et al., 2017; Paterno et al., 2010; Webster et al., 2014).

29The limb symmetry index (LSI) of quadriceps strength is a common criterion for RTS after ACLR (Webster & Hewett, 2019). However, conflicting results have been shown 3031regarding the association between LSI of quadriceps strength and the risk of second ACL injury 32(Beischer et al., 2020; Grindem et al., 2016). Therefore, evaluation of knee kinematics during 33 landing has been recommended to detect functional deficits in addition to quadriceps strength 34(Ithurburn et al., 2015; Palmieri-Smith & Lepley, 2015). Asymmetric landing mechanics and large knee valgus motion were proposed to be risk factors for a second ACL injury (Paterno et 35al., 2010). 36

37Symmetry in knee kinematics during landing could be improved by obtaining sufficient quadriceps strength (Ithurburn et al., 2015; Palmieri-Smith & Lepley, 2015). However, even 38 though athletes showed a greater than 90% LSI for quadriceps strength, athletes after ACLR 39showed more asymmetry in knee flexion excursion than healthy controls (Ithurburn et al., 402015). Therefore, good quadriceps strength may not be a sufficient condition to restore 41symmetrical knee flexion motion during landing. In addition, although knee flexion motion is 4243important to control knee valgus motion in healthy athletes (Pollard et al., 2010), the relationship between knee valgus motion and quadriceps strength after ACLR is unclear. On 44the other hand, longitudinal studies showed that knee kinematics during landing could be 45

improved with the postoperative period, while these studies did not examine longitudinal
changes in quadriceps strength (Hofbauer et al., 2014; Renner et al., 2018). Therefore, whether
knee kinematics during landing were improved by postoperative rehabilitation periods or by
improving quadriceps strength is unclear.

Most athletes are allowed to RTS between 6 and 12 months after ACLR (Barber-Westin 50& Noves, 2011). Some studies have shown that delayed RTS could reduce the risk of a second 5152injury (Beischer et al., 2020; Dekker et al., 2017; Grindem et al., 2016). A second ACL injury and other knee injuries were decreased when RTS was later than 9 months postoperatively 5354(Beischer et al., 2020; Grindem et al., 2016). However, it is not clear why delayed RTS reduces the risk of injury. Considering conflicting results regarding the relationship between quadriceps 55strength and the incidence of second ACL injury (Beischer et al., 2020; Grindem et al., 2016), 56longitudinal changes in the relationship between quadriceps strength and knee kinematics 57during landing will be informative to consider a safe RTS after ACLR. 58

The purpose of the present study was to investigate the longitudinal changes in the 59relationship between quadriceps strength and knee kinematics during a drop vertical jump 60 (DVJ) in young athletes from 6 to 9 and 12 months after ACLR. The hypothesis was that 61asymmetry in knee flexion and valgus motion would be observed before RTS (6 or 9 months) 62 regardless of quadriceps strength, but the LSI of quadriceps strength would affect knee 63 kinematics during these periods. In addition, symmetry in knee flexion and valgus motion was 64 restored at 12 months regardless of quadriceps strength, and there was no group difference in 65knee kinematics. 66

67

#### 68 Methods

69 Participants

70This longitudinal study enrolled patients who underwent ACLR at an orthopaedic hospital between May 2015 and April 2018 (Fig. 1). Considering the inclusion and exclusion criteria, a 71total of 50 patients were eligible, and 31 patients who underwent all testing were included in 72the present study (9 male and 22 female participants; age  $16.6 \pm 2.1$  years, height  $162.0 \pm 7.1$ 73cm, and body weight  $57.3 \pm 7.7$  kg). All the participants underwent double-bundle ACLR with 74tendon autografts of the semitendinosus and gracilis and completed a standardized 7576rehabilitation protocol in which participants started running at 12 weeks and jump landing with submaximal effort at 5 months. The participants started sports-specific drills without any 7778restrictions after 6 months and were allowed to RTS at 9 months. They were recommended to continue rehabilitation visits at least once a month and to continue sports-specific drills on the 79fields even after RTS. All participants signed informed consent forms, and this study was 80 81 approved by the Institutional Review Board of the Faculty of Health Sciences, Hokkaido 82 University (Approval number: 19-41).

83

#### 84 Procedures

#### 85 Drop vertical jump (DVJ) testing

A 5-minute warm-up with a stationary bicycle at a self-selected pace was performed. Markers 86 were placed on the anterior superior iliac spine (ASIS), greater trochanter, lateral femoral 87 epicondyle, patella, lateral malleolus and centre of the ankle joint defined as the midpoint 88 89 between the medial and lateral malleoli. Then, the participants performed the DVJ task. The participants dropped off a 30-cm-high box and performed a maximal vertical jump upon 90 landing. The trials were recorded using two video cameras (HDR PJ540 and HDR CX450, 9192Sony Corp., Tokyo, Japan) at 60 Hz. Each camera recorded frontal and sagittal views at a height of 1.0 m and at 3.7 m away from the landing point. After 3 successful trials were recorded, the 93

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94 contralateral side of the sagittal view was also recorded. A total of 3 trials were recorded for
95 the sagittal plane, and 6 trials were recorded for the frontal plane.

Knee kinematics were analysed by a single researcher (T.I.) using Dartfish Software 9 96 (Dartfish, Fribourg, Switzerland). The knee flexion angle was formed by markers of the greater 97 trochanter, lateral femoral epicondyle and lateral malleoli in the sagittal view (Gokeler et al., 982015). Knee valgus motion was evaluated using the frontal-plane projection angle (FPPA), 99 100which was formed by markers on the ASIS, centre of the patella and ankle joint centre (Herrington & Munro, 2010). The angular excursions of knee flexion and FPPA were calculated 101102from initial contact (IC) to peak knee flexion. The intratester reliability of each joint angle measurement was assessed using the intraclass correlation coefficient (ICC) and typical errors 103 104 (Hopkins, 2000). The ICCs (1,3) were 0.995 (95% CI: 0.977–0.999) for knee flexion excursion 105and 0.997 (95% CI: 0.988-0.999) for FPPA excursion. Typical errors were 0.44° for knee flexion excursion and 0.41° for FPPA excursion. 106

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# 108 Quadriceps strength testing

109 Quadriceps strength testing was conducted after the DVJ assessment. Isokinetic quadriceps strength was assessed using a dynamometer (Biodex System 3, Biodex Medical Systems, Inc., 110 Shirley, NY). The participants were secured to the dynamometer with their hips flexed to 90°. 111 112The concentric strength of the quadriceps and hamstring was tested at a velocity of 60°/s. 113Isokinetic testing at 60°/s is commonly used as a clinical assessment for muscle strength recovery (Petersen et al., 2014). In addition, the deficits in quadriceps strength of the involved 114limb were more apparent with slower movement speed than faster speed (Hsiao et al., 2014). 115116 Participants performed 5 repetitions with maximum effort after some practice trials. The peak torque was obtained for each limb, and the LSI was calculated as the percentage of the peak 117torque in the involved limb to that in the uninvolved limb. 118

119

## 120 Statistical analysis

121 A medium effect size was estimated for interaction effects on knee flexion excursion based on 122 pilot testing. A total of 20 participants were needed to achieve a significance ( $\alpha$ ), statistical 123 power (1 -  $\beta$ ) and effect size (*partial*  $\eta^2$ ) of 0.05, 0.8 and 0.1, respectively.

124Participants were divided into two subgroups for each postoperative period. Participants125with an LSI of quadriceps strength  $\geq 90\%$  were in the high-quadriceps (HQ) group, and < 90%126were in the low-quadriceps (LQ) group. Two-way mixed model analysis of variance (ANOVA)127was performed to examine the effects of group and limb on knee flexion and FPPA excursions.128Bonferroni tests were used for post hoc comparisons. The statistical significance level was set129at P < 0.05. These statistical analyses were performed using IBM SPSS Statistics 22 software130(IBM, Armonk, NY, USA).

131

# 132 **Results**

The number of participants at each time point is shown in Table 1. At 6 months, the involved limb showed significantly smaller knee flexion excursion than the uninvolved limb independent of the group (95% CI: 4.0–9.4°) (Fig. 2A). In contrast, there was no significant effect of group or interaction. The LQ group demonstrated greater FPPA excursion than the HQ group (95% CI: 0.1–15.2°) (Fig. 2B). There was no significant limb or interaction effect.

At 9 months, significant interaction and limb effects on knee flexion excursion were found. The LQ group demonstrated significantly smaller knee flexion excursion in the involved limb than the uninvolved limb (P < 0.001, 95% CI: 3.1–9.1°), while interlimb differences for the HQ group were not found (P = 0.158, 95% CI: -0.7–4.4°) (Fig. 3A). There was no significant main effect or interaction effect on FPPA excursion (Fig. 3B). At 12 months, no interlimb differences in knee flexion excursion were found (Fig. 4A). There was also no significant group effect or interaction on knee flexion excursion. Similarly, there was no significant main effect or interaction effect on FPPA excursion (Fig. 4B).

146

# 147 **Discussion**

The present study showed that knee flexion excursion was significantly smaller in the involved 148limb than in the uninvolved limb at 6 months regardless of quadriceps strength. At 9 months, 149asymmetry in knee flexion excursion was found only for the LQ group. On the other hand, no 150interlimb difference in knee flexion excursion was found at 12 months regardless of quadriceps 151strength group. Furthermore, FPPA excursion was significantly greater for the LQ group than 152for the HQ group only at 6 months. These present findings indicate that improvement in knee 153154kinematics during a DVJ needs the postoperative period in addition to quadriceps strength. Therefore, the hypothesis was partly supported. 155

156The present study first showed that only an LSI of quadriceps strength greater than 90% was not a sufficient condition to restore symmetrical knee flexion motion during a DVJ at 6 157months after ACLR. The interlimb difference in knee flexion excursion during a DVJ could be 158more sensitive in detecting functional deficits than the LSI of quadriceps strength at 6 months 159after ACLR. The participants started sports-specific programmes from 6 months 160 postoperatively. Therefore, recovery of neuromuscular control during jump landing may be 161insufficient to restore symmetrical knee flexion motion at 6 months. The present findings are 162supported by previous longitudinal studies that showed that an interlimb difference in the peak 163knee flexion angle during landing was found soon after the start of jump-landing training but 164not at later periods (Hofbauer et al., 2014; Renner et al., 2018). These present and previous 165findings indicate that other functional factors should be restored for symmetrical knee flexion 166 167motion after ACLR rather than recovery in quadriceps strength greater than 90% of the LSI.

168At 9 months, a significant interlimb difference in knee flexion excursion was found only in the LQ group but not in the HQ group. These findings indicate that the rehabilitation time 169required to restore symmetrical knee flexion motion is shorter in those who have symmetrical 170quadriceps strength than in those who have substantial quadriceps strength deficits. In a 171previous study on healthy athletes, strength training alone did not change jump-landing 172mechanics (Herman et al., 2008). However, strength training enhanced the effectiveness of a 173174session of jump-landing training on improvements in landing mechanics (Herman et al., 2009). These studies support the present findings that quadriceps strength affects the rehabilitation 175176time to restore symmetrical knee flexion motion during landing after ACLR. The present findings were also consistent with previous studies showing that a smaller LSI of quadriceps 177strength was associated with a smaller LSI of knee flexion excursion during a landing just after 178179clearance to RTS (Ithurburn et al., 2015; Palmieri-Smith & Lepley, 2015).

180 At 12 months, neither the HQ nor the LQ group showed significant interlimb differences in knee flexion excursion. This is the first study showing that symmetrical knee flexion 181excursion during a DVJ was restored at 12 months after ACLR, even for those with a less than 18290% LSI quadriceps strength. Quadriceps strength symmetry often does not recover even 2 183years after ACLR (Petersen et al., 2014). However, the present results suggest that long-term 184rehabilitation to restore symmetry in knee flexion motion during a DVJ is effective even for 185those with substantial quadriceps strength deficits. A previous study showed no interlimb 186187difference in knee flexion excursion during a DVJ regardless of quadriceps strength for athletes 188 after RTS (Schmitt et al., 2015). In addition, longitudinal studies showed that symmetry in the knee flexion angle had been restored at 12 months (Hofbauer et al., 2014; Renner et al., 2018). 189190 Thus, the present and previous findings indicate that the asymmetry in knee flexion motion during landing was restored by 12 months after ACLR, even for those with substantial 191quadriceps strength deficits. 192

193The results of FPPA excursion tended to be different from those of knee flexion motion. The HQ group at 6 months showed significantly smaller FPPA excursion than the LQ group. 194 However, contrary to the hypothesis, there was no interlimb difference in knee valgus motion 195196 in the LO group at 6 months, even though the LO group showed a significant interlimb difference in knee flexion motion. Therefore, quadriceps strength after ACLR may not 197influence asymmetry in knee valgus motion during a DVJ. After 9 months, there was no group 198199or interlimb difference in knee valgus motion. These findings suggest that knee valgus motion decreased with the postoperative period in the LQ group, which supports previous findings that 200201knee valgus excursion was smaller at 12 months than at 6 months after ACLR (Renner et al., 2018). 202

Concerning clinical application, even though the LSI of quadriceps strength was 90% or 203204greater, knee flexion motion asymmetry was detected at 6 months, and symmetry was restored 205between 6 and 9 months. Therefore, it is better to avoid early RTS by considering only the LSI recovery of quadriceps strength. Asymmetrical landing mechanics during landing are 206considered one of the risk factors for a second ACL injury (Paterno et al., 2010). A previous 207study showed that the risk of a second ACL injury was higher in athletes who returned within 2089 months regardless of quadriceps strength (Beischer et al., 2020). On the other hand, the LQ 209 group showed asymmetric knee flexion motion at 9 months but not at 12 months and showed 210211larger knee valgus motion than the HQ group at 6 months. Therefore, RTS for athletes with 212substantial quadriceps strength deficits should be delayed until after 9 months, preferably until 12 months. To safely RTS within 6 to 12 months after ACLR, knee kinematics during landing 213in addition to quadriceps strength should be screened. 214

There are some limitations. First, the participants were enrolled from a single hospital. Therefore, the results based on the postoperative period may be different in other rehabilitation progression protocols. Second, the present findings may be limited to double-leg landing tasks. A systematic review regarding landing mechanics after ACLR suggested that the landing strategy may differ between double-leg and single-leg tasks (Lepley & Kuenze, 2018). Finally, a kinetic analysis was not included in the present study. Kinetic asymmetry can persist longer than kinematic asymmetry (Ithurburn et al., 2019).

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232

# 223 Conclusions

The relationship between quadriceps strength and knee kinematics during a DVJ in young 224athletes after ACLR depends on the postoperative period. A certain time period of jump-landing 225rehabilitation is required to acquire symmetrical knee flexion motion even for athletes without 226substantial quadriceps strength deficits, although athletes without quadriceps strength deficits 227need a shorter period to acquire symmetrical knee flexion excursion than those with quadriceps 228229strength deficits. The present findings suggest that improvement in knee kinematics during a DVJ requires both a rehabilitation period as well as quadriceps strength. Knee kinematics 230231during landing in addition to quadriceps strength should be evaluated before RTS after ACLR.

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- **Declarations**
- 237 No potential competing interests were reported by the authors.

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	6 months		9 months		12 months	
-	HQ	LQ	HQ	LQ	HQ	LQ
Sex (male/female)	7/8	2/14	8/10	1/12	9/13	0/9
LSI of quadriceps	101.6	76.7	98.9	85.6	98.6	85.6
strength (%) <sup>a</sup>	(5.7)	(10.0)	(4.8)	(7.9)	(6.8)	(4.5)
LSI of hamstring	92.6	86.7	98.1	88.8	94.3	90.6
strength (%)	(9.9)	(20.0)	(8.8)	(10.2)	(12.7)	(8.0)
LSI of H/Q ratio	90.2	114.9	99.4	108.7	96.2	105.2
(%)	(8.5)	(29.0)	(10.9)	(17.5)	(13.6)	(11.0)

**Table 1**. The number of participants and quadriceps and hamstring strength in each group.

<sup>a</sup>Mean (SD)

LSI: limb symmetry index, H/Q ratio: hamstring/quadriceps strength ratio, HQ: high-

quadriceps group, LQ: low-quadriceps group

# **Figure captions**

Fig. 1 Flow chart for enrolment of participants

Fig. 2 Comparison of knee flexion excursion and frontal-plane projection angle (FPPA) excursion between the high-quadriceps strength group (HQ) and the low-quadriceps strength group (LQ) at 6 months postoperatively. \*indicates significant differences in post hoc test (P < 0.05).

Fig. 3 Comparison of knee flexion excursion and frontal-plane projection angle (FPPA) excursion between the high-quadriceps strength group (HQ) and the low-quadriceps strength group (LQ) at 9 months postoperatively. \*indicates a significant difference in post hoc test (P < 0.05).

**Fig. 4** Comparison of knee flexion excursion and frontal-plane projection angle (FPPA) excursion between the high-quadriceps strength group (HQ) and the low-quadriceps strength group (LQ) at 12 months postoperatively.



A Limb

Limb effect: *P* < 0.001, partial  $\eta^2$  = 0.472 Group effect: *P* = 0.958, partial  $\eta^2$  < 0.001 Interaction: *P* = 0.441, partial  $\eta^2$  = 0.021 Limb effect: P = 0.716, partial  $\eta^2 = 0.005$  **Group effect:** P = 0.048, partial  $\eta^2 = 0.128$ Interaction: P = 0.872, partial  $\eta^2 = 0.001$ 



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Fig.3

Limb effect: *P* < 0.001, partial  $\eta^2$  = 0.366 Group effect: *P* = 0.868, partial  $\eta^2$  = 0.001 Interaction: *P* = 0.035, partial  $\eta^2$  = 0.145 Limb effect: P = 0.185, partial  $\eta^2 = 0.060$ Group effect: P = 0.599, partial  $\eta^2 = 0.010$ Interaction: P = 0.786, partial  $\eta^2 = 0.003$ 



Β

Limb effect: P = 0.108, partial  $\eta^2 = 0.087$ Group effect: P = 0.544, partial  $\eta^2 = 0.013$ Interaction: P = 0.688, partial  $\eta^2 = 0.006$ 

Fig.4

Limb effect: P = 0.343, partial  $\eta^2 = 0.031$ Group effect: P = 0.127, partial  $\eta^2 = 0.078$ Interaction: P = 0.841, partial  $\eta^2 = 0.001$ 



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