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

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Abstract

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 reconstruction (ACLR) in 9 male and 22 female athletes (16.6 ± 2.1 years old). Isokinetic 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 was significantly smaller in the involved limb than in the uninvolved limb independent of quadriceps strength (56.7° ± 9.3°, 63.4° ± 11.4°, $P < 0.001$). At 9 months, only the low quadriceps strength group demonstrated a similar interlimb difference (57.2°± 12.3°, 63.3° ± 10.5°, $P < 0.001$). At 12 months, there was no significant interlimb difference in knee flexion excursion regardless of quadriceps strength. These findings indicate that restoration in symmetrical knee flexion excursion during a DVJ requires rehabilitation as well as quadriceps strength.

Keywords: landing, symmetry, knee extensor strength, return to sports, second injury

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).

The limb symmetry index (LSI) of quadriceps strength is a common criterion for RTS after ACLR (Webster & Hewett, 2019). However, conflicting results have been shown regarding the association between LSI of quadriceps strength and the risk of second ACL injury (Beischer et al., 2020; Grindem et al., 2016). Therefore, evaluation of knee kinematics during landing has been recommended to detect functional deficits in addition to quadriceps strength (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 al., 2010).

Symmetry in knee kinematics during landing could be improved by obtaining sufficient quadriceps strength (Ithurburn et al., 2015; Palmieri-Smith & Lepley, 2015). However, even though athletes showed a greater than 90% LSI for quadriceps strength, athletes after ACLR showed more asymmetry in knee flexion excursion than healthy controls (Ithurburn et al., 2015). Therefore, good quadriceps strength may not be a sufficient condition to restore symmetrical knee flexion motion during landing. In addition, although knee flexion motion is important 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 the other hand, longitudinal studies showed that knee kinematics during landing could be 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 & Noyes, 2011). Some studies have shown that delayed RTS could reduce the risk of a second injury (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 (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 strength and the incidence of second ACL injury (Beischer et al., 2020; Grindem et al., 2016), longitudinal changes in the relationship between quadriceps strength and knee kinematics during landing will be informative to consider a safe RTS after ACLR.

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

Methods

Participants

This 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 total of 50 patients were eligible, and 31 patients who underwent all testing were included in the present study (9 male and 22 female participants; age 16.6 ± 2.1 years, height 162.0 ± 7.1 cm, and body weight 57.3 ± 7.7 kg). All the participants underwent double-bundle ACLR with tendon autografts of the semitendinosus and gracilis and completed a standardized rehabilitation 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 restrictions 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 fields even after RTS. All participants signed informed consent forms, and this study was approved by the Institutional Review Board of the Faculty of Health Sciences, Hokkaido University (Approval number: 19-41).

Procedures

Drop vertical jump (DVJ) testing

A 5-minute warm-up with a stationary bicycle at a self-selected pace was performed. Markers were placed on the anterior superior iliac spine (ASIS), greater trochanter, lateral femoral epicondyle, patella, lateral malleolus and centre of the ankle joint defined as the midpoint 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 landing. The trials were recorded using two video cameras (HDR PJ540 and HDR CX450, Sony 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 contralateral side of the sagittal view was also recorded. A total of 3 trials were recorded for 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 (Dartfish, Fribourg, Switzerland). The knee flexion angle was formed by markers of the greater trochanter, lateral femoral epicondyle and lateral malleoli in the sagittal view (Gokeler et al., 2015). Knee valgus motion was evaluated using the frontal-plane projection angle (FPPA), which 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 from 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 (Hopkins, 2000). The ICCs (1,3) were 0.995 (95% CI: 0.977–0.999) for knee flexion excursion and 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.

Quadriceps strength testing

Quadriceps strength testing was conducted after the DVJ assessment. Isokinetic quadriceps strength was assessed using a dynamometer (Biodex System 3, Biodex Medical Systems, Inc., Shirley, NY). The participants were secured to the dynamometer with their hips flexed to 90°. The concentric strength of the quadriceps and hamstring was tested at a velocity of 60°/s. Isokinetic 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 limb were more apparent with slower movement speed than faster speed (Hsiao et al., 2014). 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 torque in the involved limb to that in the uninvolved limb.

Statistical analysis

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

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

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).

Discussion

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

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

At 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 required to restore symmetrical knee flexion motion is shorter in those who have symmetrical quadriceps strength than in those who have substantial quadriceps strength deficits. In a previous study on healthy athletes, strength training alone did not change jump-landing mechanics (Herman et al., 2008). However, strength training enhanced the effectiveness of a session 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 time 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 strength was associated with a smaller LSI of knee flexion excursion during a landing just after clearance to RTS (Ithurburn et al., 2015; Palmieri-Smith & Lepley, 2015).

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 excursion during a DVJ was restored at 12 months after ACLR, even for those with a less than 90% LSI quadriceps strength. Quadriceps strength symmetry often does not recover even 2 years after ACLR (Petersen et al., 2014). However, the present results suggest that long-term rehabilitation to restore symmetry in knee flexion motion during a DVJ is effective even for those with substantial quadriceps strength deficits. A previous study showed no interlimb difference in knee flexion excursion during a DVJ regardless of quadriceps strength for athletes 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). 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 quadriceps strength deficits.

The 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. However, contrary to the hypothesis, there was no interlimb difference in knee valgus motion in the LQ group at 6 months, even though the LQ group showed a significant interlimb difference in knee flexion motion. Therefore, quadriceps strength after ACLR may not influence asymmetry in knee valgus motion during a DVJ. After 9 months, there was no group or 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 knee valgus excursion was smaller at 12 months than at 6 months after ACLR (Renner et al., 2018).

Concerning clinical application, even though the LSI of quadriceps strength was 90% or greater, knee flexion motion asymmetry was detected at 6 months, and symmetry was restored between 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 considered one of the risk factors for a second ACL injury (Paterno et al., 2010). A previous study showed that the risk of a second ACL injury was higher in athletes who returned within 9 months regardless of quadriceps strength (Beischer et al., 2020). On the other hand, the LQ group showed asymmetric knee flexion motion at 9 months but not at 12 months and showed larger knee valgus motion than the HQ group at 6 months. Therefore, RTS for athletes with substantial 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 in addition to quadriceps strength should be screened.

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).

Conclusions

The relationship between quadriceps strength and knee kinematics during a DVJ in young athletes after ACLR depends on the postoperative period. A certain time period of jump-landing rehabilitation is required to acquire symmetrical knee flexion motion even for athletes without substantial quadriceps strength deficits, although athletes without quadriceps strength deficits need a shorter period to acquire symmetrical knee flexion excursion than those with quadriceps strength 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 during landing in addition to quadriceps strength should be evaluated before RTS after ACLR.

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Declarations

No potential competing interests were reported by the authors.

References

Barber-Westin, S. D., & Noyes, F. R. (2011). Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, *27*(12), 1697-1705.

Beischer, S., Gustavsson, L., Senorski, E. H., Karlsson, J., Thomeé, C., Samuelsson, K., & Thomeé, R. (2020). Young Athletes Who Return to Sport Before 9 Months After Anterior Cruciate Ligament Reconstruction Have a Rate of New Injury 7 Times That of Those Who Delay Return. *J Orthop Sports Phys Ther*, *50*(2), 83-90.

Dekker, T. J., Godin, J. A., Dale, K. M., Garrett, W. E., Taylor, D. C., & Riboh, J. C. (2017). Return to Sport After Pediatric Anterior Cruciate Ligament Reconstruction and Its Effect on Subsequent Anterior Cruciate Ligament Injury. *The Journal of Bone and Joint Surgery. American Volume*, *99*(11), 897-904.

Gokeler, A., Benjaminse, A., Welling, W., Alferink, M., Eppinga, P., & Otten, B. (2015). The effects of attentional focus on jump performance and knee joint kinematics in patients after ACL reconstruction. *Physical Therapy in Sport*, *16*(2), 114-120.

Graziano, J., Chiaia, T., de Mille, P., Nawabi, D. H., Green, D. W., & Cordasco, F. A. (2017). Return to Sport for Skeletally Immature Athletes After ACL Reconstruction: Preventing a Second Injury Using a Quality of Movement Assessment and Quantitative Measures to Address Modifiable Risk Factors. *Orthopaedic Journal of Sports Medicine*, *5*(4), 2325967117700599.

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *British Journal of Sports Medicine*, *50*(13), 804-808.

Herman, D. C., Oñate, J. A., Weinhold, P. S., Guskiewicz, K. M., Garrett, W. E., Yu, B., & Padua, D. A. (2009). The effects of feedback with and without strength training on lower extremity biomechanics. *The American Journal of Sports Medicine*, *37*(7), 1301-1308.

Herman, D. C., Weinhold, P. S., Guskiewicz, K. M., Garrett, W. E., Yu, B., & Padua, D. A. (2008). The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *The American Journal of Sports Medicine*, *36*(4), 733-740.

Herrington, L., & Munro, A. (2010). Drop jump landing knee valgus angle; normative data in a physically active population. *Physical Therapy in Sport*, *11*(2), 56-59.

Hofbauer, M., Thorhauer, E. D., Abebe, E., Bey, M., & Tashman, S. (2014). Altered tibiofemoral kinematics in the affected knee and compensatory changes in the contralateral knee after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, *42*(11), 2715-2721.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine (Auckland, N.Z.)*, *30*(1), 1-15.

Hsiao, S.-F., Chou, P.-H., Hsu, H.-C., & Lue, Y.-J. (2014). Changes of muscle mechanics associated with anterior cruciate ligament deficiency and reconstruction. *Journal of Strength and Conditioning Research*, *28*(2), 390-400.

Ithurburn, M. P., Paterno, M. V., Ford, K. R., Hewett, T. E., & Schmitt, L. C. (2015). Young Athletes With Quadriceps Femoris Strength Asymmetry at Return to Sport After Anterior Cruciate Ligament Reconstruction Demonstrate Asymmetric Single-Leg Drop-Landing Mechanics. *The American Journal of Sports Medicine*, *43*(11), 2727-2737.

Ithurburn, M. P., Paterno, M. V., Thomas, S., Pennell, M. L., Evans, K. D., Magnussen, R. A., & Schmitt, L. C. (2019). Change in Drop-Landing Mechanics Over 2 Years in Young Athletes After Anterior Cruciate Ligament Reconstruction. *The American Journal of*

Sports Medicine, *47*(11), 2608-2616.

Lepley, A. S., & Kuenze, C. M. (2018). Hip and Knee Kinematics and Kinetics During Landing Tasks After Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-Analysis. *Journal of Athletic Training*, *53*(2), 144-159.

Palmieri-Smith, R. M., & Lepley, L. K. (2015). Quadriceps Strength Asymmetry After Anterior Cruciate Ligament Reconstruction Alters Knee Joint Biomechanics and Functional Performance at Time of Return to Activity. *The American Journal of Sports Medicine*, *43*(7), 1662-1669.

Paterno, M. V., Huang, B., Thomas, S., Hewett, T. E., & Schmitt, L. C. (2017). Clinical Factors That Predict a Second ACL Injury After ACL Reconstruction and Return to Sport: Preliminary Development of a Clinical Decision Algorithm. *Orthopaedic Journal of Sports Medicine*, *5*(12), 2325967117745279.

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical Measures During Landing and Postural Stability Predict Second Anterior Cruciate Ligament Injury After Anterior Cruciate Ligament Reconstruction and Return to Sport. *The American Journal of Sports Medicine*, *38*(10), 1968-1978.

Petersen, W., Taheri, P., Forkel, P., & Zantop, T. (2014). Return to play following ACL reconstruction: a systematic review about strength deficits. *Archives of Orthopaedic and Trauma Surgery*, *134*(10), 1417-1428.

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics (Bristol, Avon)*, *25*(2), 142-146.

Renner, K. E., Franck, C. T., Miller, T. K., & Queen, R. M. (2018). Limb asymmetry during recovery from anterior cruciate ligament reconstruction. *Journal of Orthopaedic*

Research, *36*(7), 1887-1893.

Schmitt, L. C., Paterno, M. V., Ford, K. R., Myer, G. D., & Hewett, T. E. (2015). Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. *Medicine and Science in Sports and Exercise*, *47*(7), 1426-1434.

Webster, K. E., Feller, J. A., Leigh, W. B., & Richmond, A. K. (2014). Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, *42*(3), 641-647.

Webster, K. E., & Hewett, T. E. (2019). What is the Evidence for and Validity of Return-to-Sport Testing after Anterior Cruciate Ligament Reconstruction Surgery? A Systematic Review and Meta-Analysis. *Sports Medicine (Auckland, N.Z.)*, *49*(6), 917-929.

Wiggins, A. J., Grandhi, R. K., Schneider, D. K., Stanfield, D., Webster, K. E., & Myer, G. D. (2016). Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis. *The American Journal of Sports Medicine*, *44*(7), 1861-1876.

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

	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 strength (%)[a]	101.6 (5.7)	76.7 (10.0)	98.9 (4.8)	85.6 (7.9)	98.6 (6.8)	85.6 (4.5)
LSI of hamstring strength (%)	92.6 (9.9)	86.7 (20.0)	98.1 (8.8)	88.8 (10.2)	94.3 (12.7)	90.6 (8.0)
LSI of H/Q ratio (%)	90.2 (8.5)	114.9 (29.0)	99.4 (10.9)	108.7 (17.5)	96.2 (13.6)	105.2 (11.0)

[a]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.

Fig.1

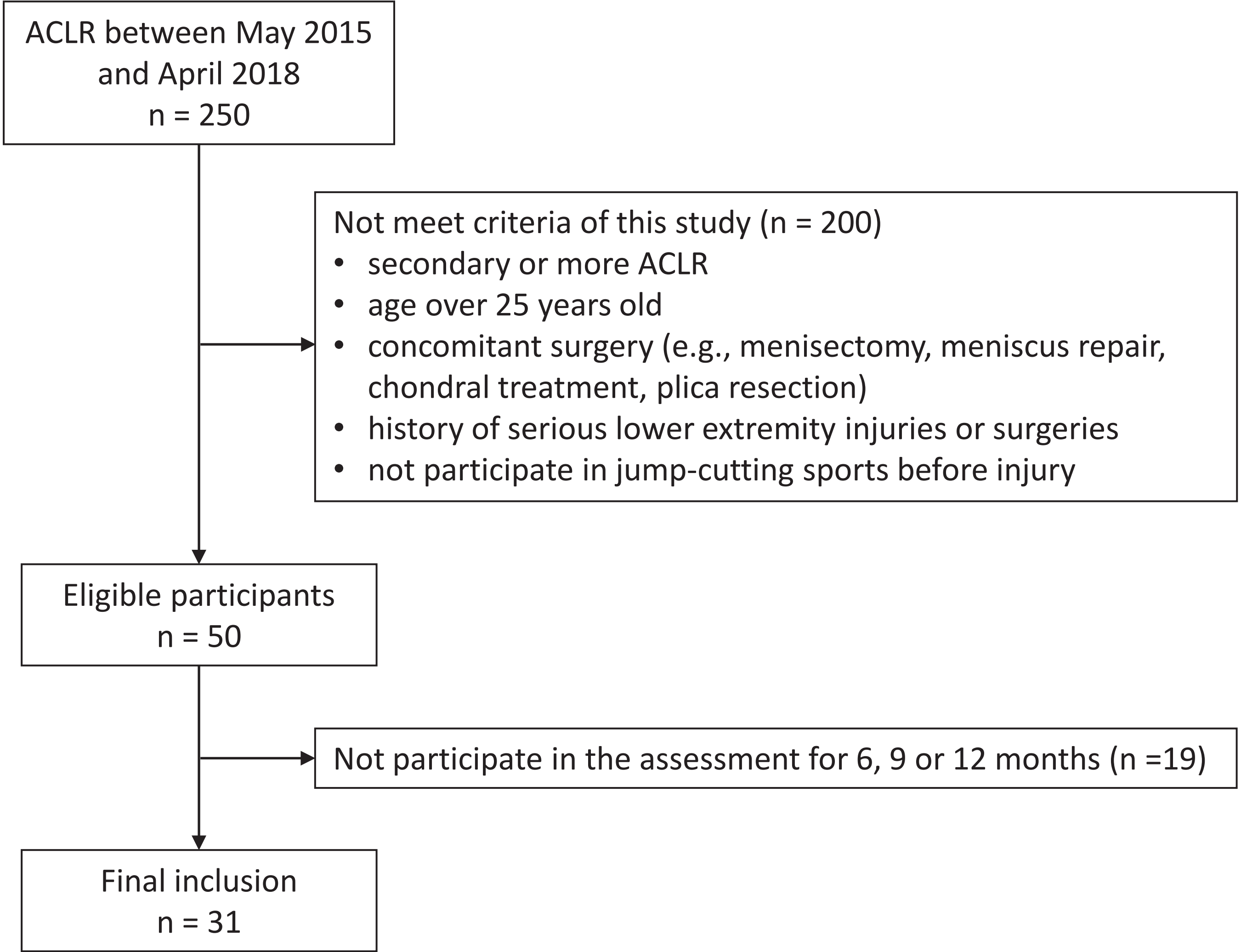
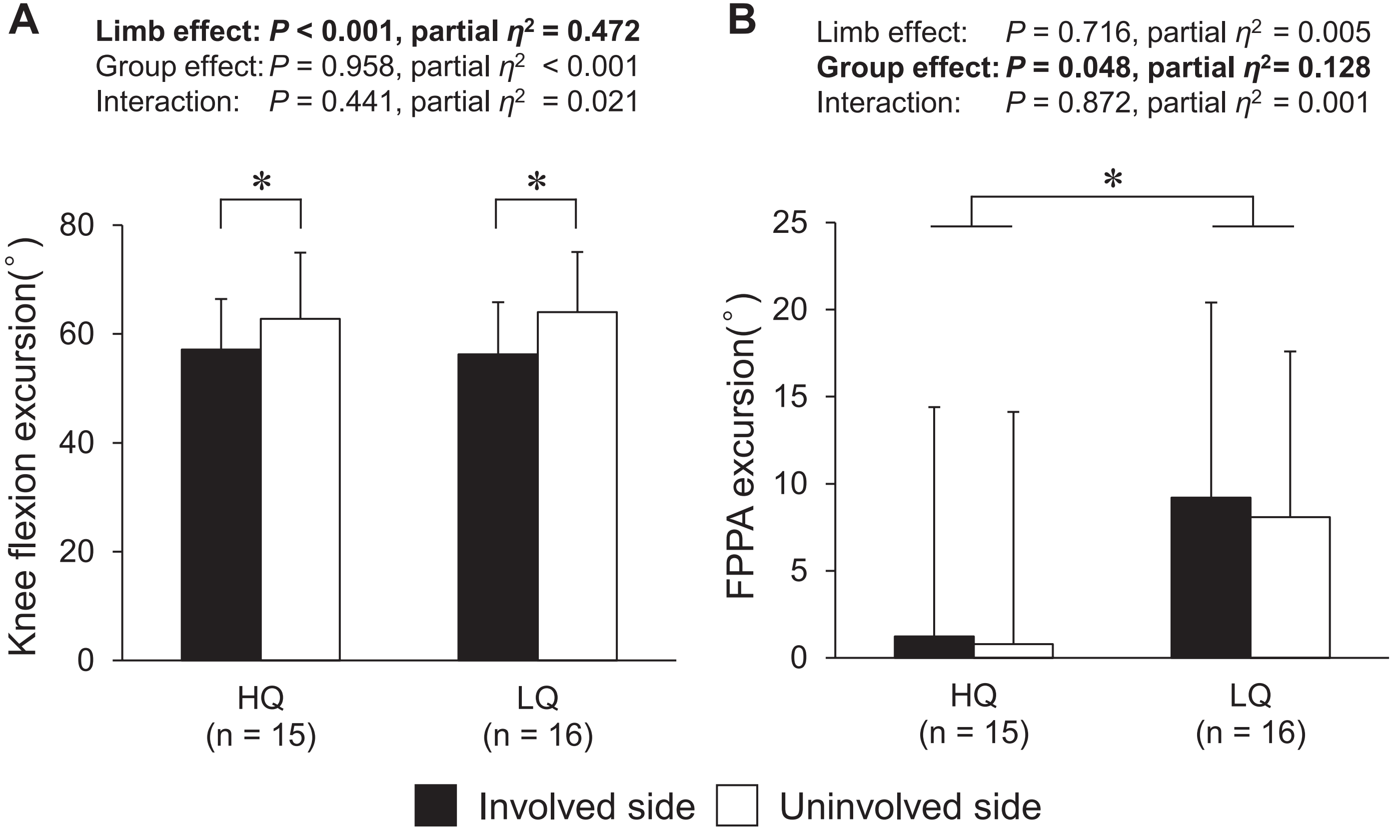
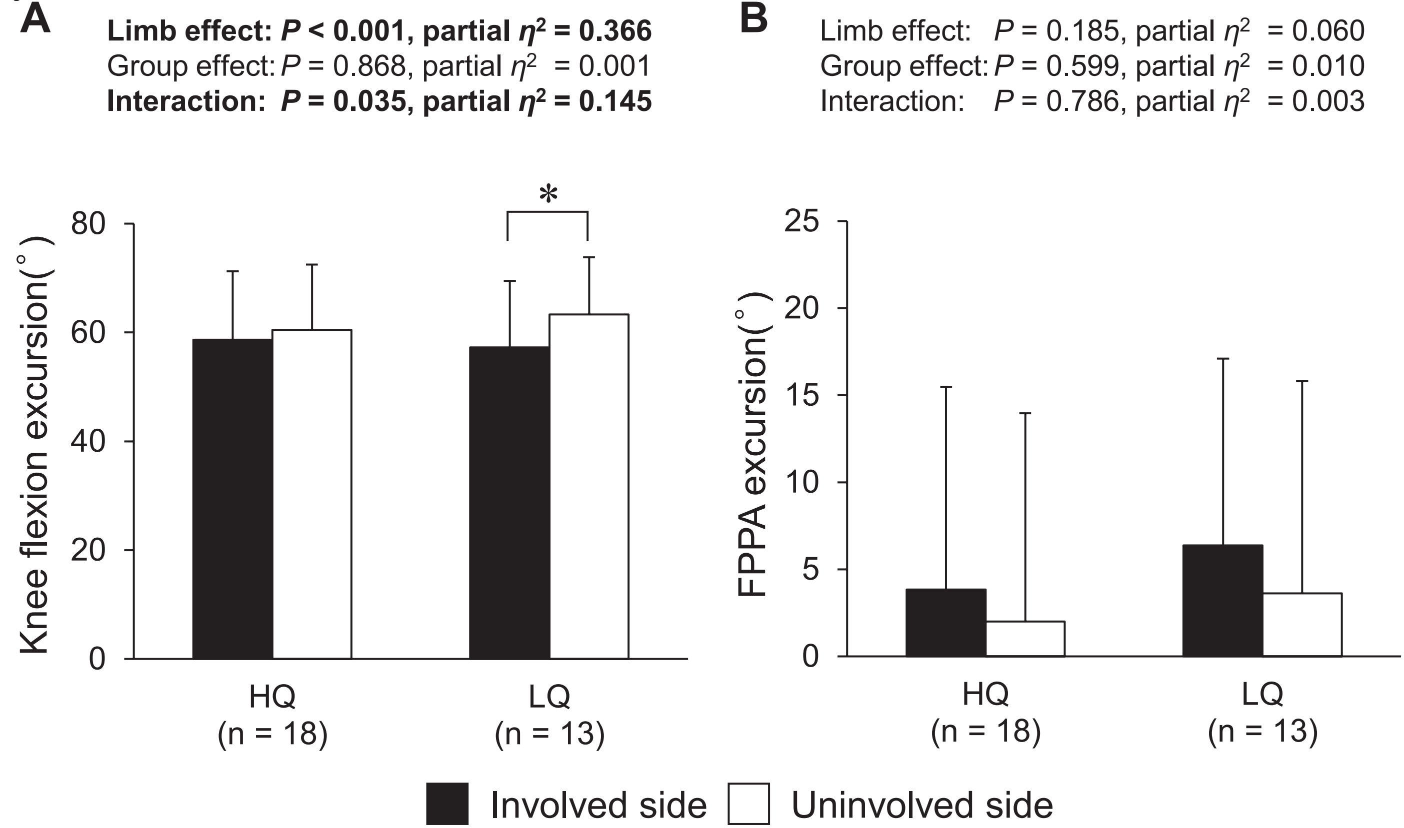

ACLR between May 2015 and April 2018
n = 250
Not meet criteria of this study (n = 200)
secondary or more ACLR
age over 25 years old
concomitant surgery (e.g., menisectomy, meniscus repair, chondral treatment, plica resection)
history of serious lower extremity injuries or surgeries
not participate in jump-cutting sports before injury
Eligible participants
n = 50
Not participate in the assessment for 6, 9 or 12 months (n =19)
Final inclusion
n = 31

Fig.2



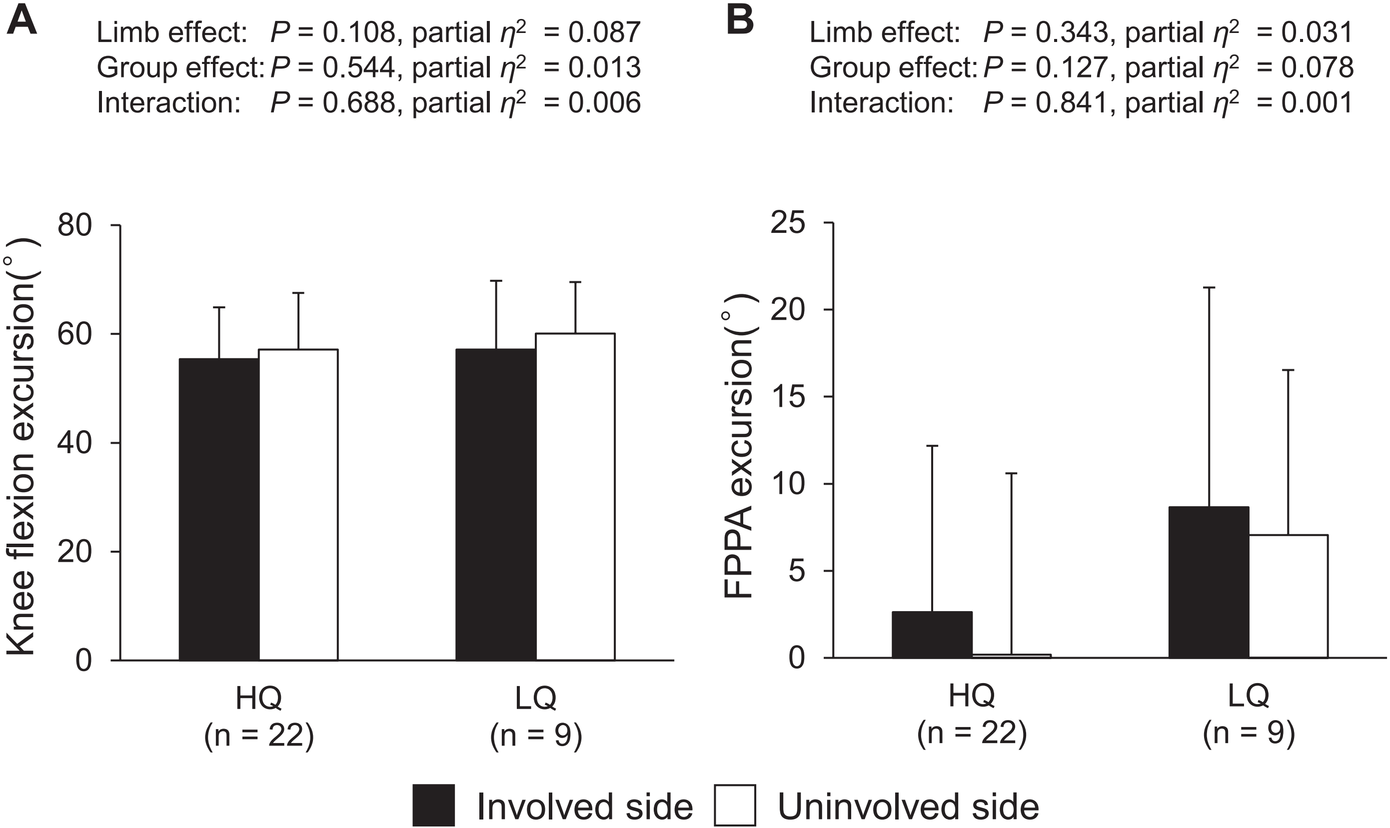
A
Limb effect: P < 0.001, partial η^2 = 0.472
Group effect: P = 0.958, partial η^2 < 0.001
Interaction: P = 0.441, partial η^2 = 0.021
*
*
Knee flexion excursion(°)
80
60
40
20
0
HQ
(n = 15)
LQ
(n = 16)
B
Limb effect: P = 0.716, partial η^2 = 0.005
Group effect: P = 0.048, partial η^2 = 0.128
Interaction: P = 0.872, partial η^2 = 0.001
*
FPPA excursion(°)
25
20
15
10
5
0
HQ
(n = 15)
LQ
(n = 16)
Involved side
Uninvolved side

Fig.3



A
Limb effect: P < 0.001, partial η2 = 0.366
Group effect: P = 0.868, partial η2 = 0.001
Interaction: P = 0.035, partial η2 = 0.145
Knee flexion excursion(°)
80
60
40
20
0
*
HQ
(n = 18)
LQ
(n = 13)
B
Limb effect: P = 0.185, partial η2 = 0.060
Group effect: P = 0.599, partial η2 = 0.010
Interaction: P = 0.786, partial η2 = 0.003
FPPA excursion(°)
25
20
15
10
5
0
HQ
(n = 18)
LQ
(n = 13)
Involved side
Uninvolved side

Fig.4


A
Limb effect: P = 0.108, partial η2 = 0.087
Group effect: P = 0.544, partial η2 = 0.013
Interaction: P = 0.688, partial η2 = 0.006
Knee flexion excursion(°)
80
60
40
20
0
HQ
(n = 22)
LQ
(n = 9)
B
Limb effect: P = 0.343, partial η2 = 0.031
Group effect: P = 0.127, partial η2 = 0.078
Interaction: P = 0.841, partial η2 = 0.001
FPPA excursion(°)
25
20
15
10
5
0
HQ
(n = 22)
LQ
(n = 9)
Involved side
Uninvolved side