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Original Article

The relationship between knee muscle strength and knee biomechanics during running at 6 and 12 months after anterior cruciate ligament reconstruction

Makoto Asaeda ^{a,b,*}, Masataka Deie ^c, Yoshifumi Kono ^b, Yukio Mikami ^{a,d},
Hiroaki Kimura ^{a,d}, Nobuo Adachi ^{a,e}^a Sports Medical Center, Hiroshima University Hospital, 1-2-3 Kasumi, Minami-ku, Hiroshima, 734-8551, Japan^b Division of Rehabilitation, Department of Clinical Practice and Support, Hiroshima University Hospital, 1-2-3 Kasumi, Minami-ku, Hiroshima, 734-8551, Japan^c Department of Orthopedic Surgery, Aichi Medical University, 1-1 Yazakokarimata, Nagakute, Aichi, 480-1195, Japan^d Department of Rehabilitation, Hiroshima University Hospital, 1-2-3 Kasumi, Minami-ku, Hiroshima, Japan^e Department of Orthopaedic Surgery, Division of Medicine, Biomedical Sciences Major, Graduate School of Biomedical and Health Sciences, Hiroshima University, 1-2-3 Kasumi, Minami-ku, Hiroshima, 734-8551, Japan

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ABSTRACT

Background: Knee joint kinematics and kinetics during running recover at 12 months, not 6 months, following anterior cruciate ligament (ACL) reconstruction surgery. Knee muscle strength is a criterion used to assess an individual's readiness to return-to-sports (RTS); however, the relationship between knee muscle strength and knee biomechanics is unclear. This study investigated the relationship between knee muscle strength and dynamic knee biomechanics during running at 6 and 12 months after ACL reconstruction surgery.

Methods: Knee joint kinematics and kinetics during running were analyzed in 21 patients (10 males, 11 females) who underwent ACL reconstruction for a unilateral ACL deficiency. Kinematics and Kinetics were measured by three-dimensional motion analysis system, and Knee flexion angle was calculated using Point cluster technique and internal extension moment was calculated by the inverse dynamics method. Patients were compared to a control group matched by age, height and weight. Isokinetic knee extension and flexion strength in ACL-reconstructed patients were measured at 6 and 12 months postsurgery, by separated gender.

Results: Knee flexion angle was significantly lower in ACL patients at 6 months postsurgery compared to the control group ($F(2, 62)=5.78, P=0.014$). There were significant lower peak knee flexion angles in male groups than female ($F(1, 62)=6.33, P<0.01$). Knee extension moments were significantly lower in both male and female ACL patients compared to the control group at 6 and 12 months postsurgery ($F(2, 62)=12.05, P<0.01(6\text{ months}), P=0.034(12\text{ months})$), and there were significant correlations with knee extension moments and maximum torque of knee extension/flexion ($P<0.05$). At 12 months after surgery, knee joint kinematics in ACL patients were restored. Both peak knee angle and knee extension moment were significantly associated with maximum knee extension/flexion torque values in female patients at 12 months postsurgery.

Conclusions: Dynamic knee biomechanics during running were not restored 6 and 12 months after ACL reconstruction both male and female. It is necessary to strengthen knee extension and flexion muscles to restore knee kinetics during running, especially female patients.

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Introduction

Anterior cruciate ligament (ACL) reconstruction provides successful clinical outcomes; however, reconstruction cannot restore

* Corresponding author. Sports Medical Center, Hiroshima University Hospital, 1-2-3 Kasumi, Minami-ku, Hiroshima, 734-8551, Japan.

E-mail address: asaeda@hiroshima-u.ac.jp (M. Asaeda).

normative knee kinematics during gait.^{1,2} Previous study showed that whether gender influenced knee joint biomechanics during gait after ACL reconstruction, and abnormal sagittal plane mechanics (high knee flexion angle and lower knee extension moment) had recovered at 12-months after reconstruction, but not at 6 months, in both male and female patients.³ Another study also found that 33% of patients had not attempted any form of sports activity in the 12 months following surgery.⁴ Permission to return to sports (RTS) is generally granted 6–9 months following surgery⁵; however, granting permission at 6 months may be too early because knee kinematics during daily and sports activities have not recovered sufficiently.^{3,6,7} This emphasizes the importance of monitoring knee sagittal biomechanics during sports activity for 12 months following ACL reconstruction surgery.

Knee muscle strength is a criterion of RTS after ACL reconstruction. Female patients who returned to their pre-injured sports level (Tegner activity scale ± 1) 10 months postsurgery had greater knee extension strength than females who did not return.⁸ Kline et al.⁹ also found that quadriceps strength at 3 months postsurgery is predictive of knee flexion excursion and knee extension moment during running at 6 months after surgery. Patients with quadriceps strength <80% of the uninjured side also had reduced knee flexion angles and moments during running at 14.3–20.8 weeks after ACL reconstruction.¹⁰ Therefore, strengthening the knee muscle is an important step for recovering knee biomechanics after ACL reconstruction, and biomechanics and effect of muscle strength is differ each gender.^{3,8} However, there were no studies about the relationship between knee muscle strength and knee biomechanics during running after ACL reconstruction, so it is important for returning sports activity that clarifying this relationship.

The purpose of this study was to investigate the relationship between knee muscle strength and dynamic knee biomechanics at 6 and 12 months after ACL reconstruction. We hypothesized that knee sagittal biomechanics during running are not sufficiently recovered in ACL reconstruction patients at 6 months postsurgery in both male and female patients. We also hypothesized that knee kinematics and kinetics are correlated with knee muscle strength, and that the abnormal knee movements may recover in association with recovering knee muscle strength by 12 months after surgery. Female group have more knee flexion angle comparing male group because previous study showed that knee flexion angle during gait in females was higher than in males.

Methods

Study participants

This was a case-control study. Prospective participants included both male and female patients who were evaluated at our clinic for a unilateral ACL injury and whose knee biomechanics during running were measured using three-dimensional motion analysis between October 2013 and September 2015. Inclusion criteria were: age <40 years; body mass index (BMI) <35 kg/m²; no evidence of knee osteoarthritis (OA) on plain radiographs; no medical documentation or radiographic evidence of tibiofemoral and patellofemoral joint cartilage (both articular cartilage and meiscus) injury from operative findings; no limitation of knee range of motion at 6- and 12-month follow-ups after ACL reconstruction; absence of self-reported knee pain or apprehension with running at 6- and 12-month follow-ups after ACL reconstruction; absence of other lower limb in both operative and contralateral side injuries or functional limitations at pre-operative and 6- and 12-month follow-ups after ACL reconstruction; attendance at 6- and 12-month follow-ups after ACL reconstruction; and absence of neurological diseases. The study group comprised 21 patients, with

10 males (ACL-M group) and 11 females (ACL-F group; Table 1). A control group comprising 21 healthy participants with no history of orthopedic injury or neurological disease, matched for age, height and weight, were recruited from the community. This group also had 10 males (Control-M group) and 11 females (Control-F group; Table 1). Running analysis and clinical assessment of knee muscle strength and anterior translation of the tibia relative to the femur were performed before surgery, and at 6 and 12 months after ACL augmentation or reconstruction. In control group, we measured only running analysis. Our study was approved by the ethics committee of our institution, and our methods conformed to the Declaration of Helsinki. All participants provided informed consent (see Tables 2–4).

Operative technique

All ACL reconstructions or augmentations were performed by experienced surgeons using previously reported surgical procedures.^{11–15} ACL augmentation was performed for cases with an ACL remnant about one-third of the original ACL, which provided a ligamentous bridge between the tibia and the femur. Augmentation was performed using a quadrupled semitendinosus tendon graft. In the absence of sufficient ACL remnant, ACL reconstruction was performed using either a single- or double-bundle technique, depending on the diameter of the quadrupled semitendinosus tendon graft and the size of tibia and femur. All operation was performed by quadrupled semitendinosus. The reconstructed knee was immobilized using a soft knee brace for 3 days after surgery. At 3 days after surgery, the patients were allowed knee ROM exercises with brace and partial weight bearing at 10 days and started full weight bearing at 17 days. After leaving hospital, they received follow-up at out-patients hospital and used brace until 3 months after surgery. Patients were allowed running at 4.5 months following surgery and sports training (such as jumping) at 10 months.

Measurement

Running analysis

Based on the point cluster technique (PCT),¹⁶ 21 skin-based reflective markers were placed on one leg of each participant (FIGURE. Supplemental 1). Static knee angles were measured before the running analysis for calculation of dynamic knee angle by the PCT. A 5-s static standing trial was also recorded, during which participants looked straight ahead with their arms folded across their chest. Running analysis was performed using a three-dimensional motion analysis system, with 16 infrared cameras capturing motion data at a sampling frequency of 100 Hz (VICON MX; Vicon Motion Systems, Oxford, UK). Cameras were calibrated prior to data collection with a mean residual error of <1.0 mm. Participants ran along a 10-m runway at a self-selected speed, maintaining a forward gaze and a natural motion of the upper limbs. For kinetic analysis, ground reaction force data was recorded at 1000 Hz using 8 force platforms (AMTI, Watertown, USA) embedded in a runway (Fig. 1). Trials were repeated until 5 full strides, defined by successful footfalls on 2 successive force platforms, were obtained. Running event was defined from the initial contact (IC), and IC was defined by a ground reaction force magnitude > 10 N.

Peak knee flexion angle during running was calculated using PCT described by Andriacchi et al.,¹⁶ in which 21 reflective markers were secured to specific locations on the lower limb being assessed. The reliability of kinematic measurements using PCT has been confirmed.^{3,17,18} Values were expressed relative to knee angles in the standing position for between-subject comparisons.

Table 1
Baseline participant characteristics.

	ACL-M (n = 10)	ACL-F (n = 11)	Control-M (n = 10)	Control-F (n = 11)	P value ACL-M vs Control-M	P value ACL-F vs Control-F	P value ACL-M vs ACL-F
Age (year)	23.9 ± 8.9	20.4 ± 8.2	21.8 ± 1.4	21.0 ± 1.5	0.478	0.806	0.356
Body height (m)	1.73 ± 0.06	1.62 ± 0.06	1.75 ± 0.05	1.59 ± 0.04	0.446	0.583	0.001
Body weight (kg)	69.6 ± 8.5	56.6 ± 5.5	65.2 ± 5.8	54.2 ± 4.6	0.193	0.278	< 0.001
Body mass index (kg/m ²)	23.4 ± 3.0	21.7 ± 2.0	21.4 ± 1.0	21.3 ± 1.2	0.055	0.364	0.032
Measurement side (left/right, n)	4/6	7/4	4/6	7/4	1.000	1.000	0.279
Reconstructive surgery (SB/SBA/DB)	1/1/8	0/7/3	—	—	—	—	0.013
Time post-injury (months)	6.2 ± 3.2	4.8 ± 3.2					0.350

Values are reported as the mean ± standard deviation; SB, single-bundle reconstruction; SBA, single-bundle augmentation; DB, double-bundle reconstruction; P values in bold type are significant.

Table 2
Knee extension and flexion strengths and anterior tibia translation (ATT) at 6 and 12 months postsurgery.

	ACL-M (n = 10)		P value	ACL-F (n = 11)		P value
	6 months postsurgery	12 months postsurgery		6 months postsurgery	12 months postsurgery	
Maximal torque of knee extension (% Nm/kg)	142.7 ± 36.7	163.3 ± 20.4	0.002	117.0 ± 32.7	137.5 ± 32.0	0.011
Affected/non-affected ratio of knee extension torque (%)	78.0 ± 12.3	88.5 ± 10.0	0.012	71.5 ± 13.1	83.9 ± 8.58	0.002
Maximal torque of knee flexion (% Nm/kg)	78.7 ± 23.5	86.9 ± 16.7	0.007	61.0 ± 16.6	73.9 ± 17.3	0.011
Affected/non-affected ratio of knee flexion torque (%)	78.5 ± 13.6	93.3 ± 14.9	< 0.001	80.0 ± 12.1	94.1 ± 7.44	0.018
Side-to-side difference in ATT (mm)	0.07 ± 0.86	1.10 ± 1.44	0.008	0.45 ± 1.58	0.76 ± 1.65	0.439

Values are reported as the mean ± standard deviation, paired *t*-test between the 6-months and 12-months postsurgery groups; P values in bold type are significant.

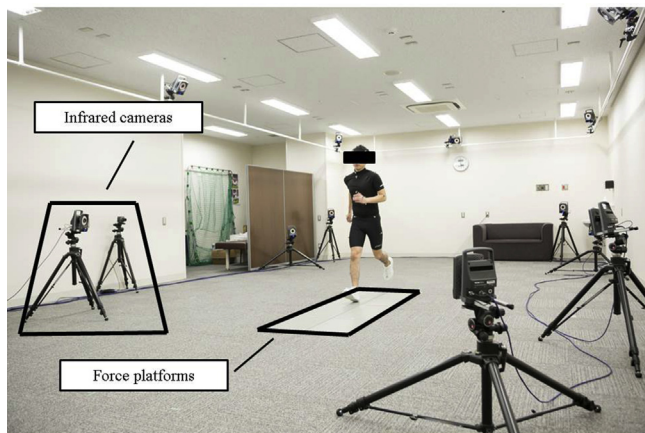


Fig. 1. Environmental measurement.

Internal knee extension moments were calculated by the inverse dynamics method using the Vicon Bodybuilder processing software (Vicon Motion Systems, Oxford, UK). The peak magnitude after IC, normalized to body weight, was used for analysis. For the analysis of knee extension moment, the position of the reflective markers was low-pass filtered (Butterworth 4th-order filter, cut-off frequency: 6 Hz) using ButterPlug plug-in software (Vaquita Software, Zaragoza, Spain).

Clinical assessment

Maximum knee extension and flexion muscle torques were measured using a Biodex Multi-Joint System isokinetic dynamometer (BIODEX Medical Systems, Shirley, New York, USA). Patients performed 5 repetitions of maximal reciprocal concentric knee extension and flexion cycles at an angular velocity of 180°/s. The maximum torque value for flexion and extension, normalized to body weight, was used as the index of muscle strength for analysis.

Anterior translation of the tibia on the femur (ATT) was

measured using a Kneelax 3 system (Monitored Rehab Systems, Haarlem, Netherlands), with an application of 133 N with the knee in 20° of flexion. The side to side difference in ATT was calculated by subtracting the value of the uninjured side from that of the injured side, with the difference in values used for analysis.

Statistical analysis

Characteristics of participants were analyzed by the independent *t*-test and chi-square test. Knee muscle strengths at 6 and 12 months postsurgery were grouped by gender and analyzed using the paired *t*-test. Two-way analysis of variance (ANOVA) was used to identify differences in knee flexion angle and knee extension moments: 2 levels of gender (male and female) X 3 groups of measurement (6, 12 months postsurgery and Control). To identify main effects, interactions and simple main effects were evaluated using a Tukey HSD analysis. Spearman's rank correlation was used to determine correlations between knee biomechanics during running and knee muscle strength grouped by gender. Statistical analyses were performed using SPSS statistical analysis software (IBM SPSS Statistics version 19.0; IBM Japan, Tokyo, Japan), with a P value < 0.05 considered significant.

Results

Participant characteristics and clinical assessment

There were no significant differences in age, height, weight and body mass index between the patient and control groups for both males and females (*P* > 0.05). There was significantly difference in reconstructive surgery between ACL-M group and ACL-F (*P* = 0.013). The maximum torque flexion and extension values were significantly improved at 12 months after surgery compared to 6 months following surgery (*P* < 0.05).

Running analysis

There was significantly difference of knee flexion angle between

Table 3

Summary of kinematics and kinetics data at 6 months and 12 months postsurgery.

	ACL-M (n = 10)		ACL-F (n = 11)		Control-M (n = 10)	Control-F (n = 11)	Gender effect F (1, 62)	Group effect F (2, 62)	Gender × group interaction F (2, 62)
	6 months postsurgery	12 months postsurgery	6 months postsurgery	12 months postsurgery					
Peak knee flexion angle (degree)	37.8 ± 4.0	41.1 ± 6.8	42.3 ± 6.7	43.0 ± 5.3	43.7 ± 5.5	47.5 ± 2.5	6.33*	5.78**	0.35
Internal knee extension moment (Nm/kg)	1.66 ± 0.43	2.01 ± 0.30	1.63 ± 0.65	2.04 ± 0.36	2.59 ± 0.75	2.28 ± 0.50	0.66	12.05***	0.64

Mean ± SD, *; $P < 0.01$ (Male vs. Female), **; $P = 0.014$ (6 months postsurgery vs. Control), ***; $P < 0.01$ (6 months postsurgery vs. Control), $P = 0.034$ (12 months postsurgery vs. Control).

6 months postsurgery and control ($P = 0.014$), and there was no significant differences in knee flexion angle between at 12 months and Control ($P > 0.05$). There were significant lower knee flexion angles in male groups than female ($P < 0.01$). About the internal knee extension moment after IC there was and significantly difference between both 6 and 12 postsurgery and control ($P < 0.01$ (6 months postsurgery vs. Control), $P = 0.034$ (12 months postsurgery vs. Control)).

Correlation with knee muscle strength

At 6 months following surgery, there was a significant correlation between the knee flexion angle and maximum torque value for flexion in female patients ($r = 0.609$, $P = 0.047$, Table 3), but not in male patients ($P > 0.05$, Table 3). There were also significant correlations between the peak internal extension moment and maximum torque value for extension in both males and females (males: $r = 0.830$, $P = 0.003$; females: $r = 0.655$, $P = 0.029$, Table 4).

At 12 months following surgery, there were significant correlations between all kinematics, and kinetic values were significantly correlated with the maximum torque values for flexion and extension in female patients ($P < 0.05$, Table 3). In male patients, there was negative correlation between the maximum torque values for extension and knee flexion angle ($r = -0.754$, $P = 0.013$, Table 4).

Discussion

The most important findings of the present study were as follows: first, both male and female patients had smaller knee flexion angle and knee extension moments during running than the control group at 6 months after surgery. Second, significantly difference in knee extension moments 12 months following surgery between the patients and the control group. Third, a significant correlation between knee muscle strength and internal knee extension moments in both males and females 6 months following surgery. Both male and female patients had smaller knee flexion

angle and knee extension moments during running than the control group at 6 months after surgery, which supports our hypothesis that knee biomechanics need longer than 6 months to recover following ACL reconstruction. Our results also support previous studies, which describe abnormal knee biomechanics during gait following ACL reconstruction.^{3,6,7} Specifically, Sigward et al.¹⁹ observed smaller knee extension moment impulse in ACL-reconstructed knees 4 months after surgery; therefore, knee kinetics during running did not recover to control levels. Lewek et al.¹⁰ also showed that inadequate quadriceps strength contributed to altered running movements in reconstructed knees with no symptoms of instability. Our patients had similar muscle strength and knee flexion angles and knee extension moments during running compared to the previous study, and we also show a significant relationship between muscle strength of knee extension and extension moment in both male and female patients. Therefore, it appears that strengthening knee muscles, quadriceps and hamstrings are important for restoring running biomechanics. Altered sagittal plane knee moment measurements recorded during a landing task were also found to predict the risk of a second ACL injury.²⁰ Although landing tasks were not undertaken in the current study, our patient group had smaller knee extension moments than the control group, which may increase their risk of secondary ACL injury. Therefore, resuming sports activities 6 months after ACL reconstruction is not recommended.

There were no significant differences in the knee flexion angles, but significantly difference in knee extension moments 12 months following surgery between the patients and the control group. These results indicate that running biomechanics did not recover between 6 and 12 months postsurgery in both male and female patients. And we showed that knee muscle strength is greater at 12 months postsurgery than at 6 months. Similarly, Lee et al.²¹ reported that quadriceps muscle strength was 70% that of the uninjured side at 6 months following surgery and increased to 80% by 12 months postsurgery. The quadriceps strength of our patients is the same value from previous study at both 6 and 12 months following surgery, so in this study, there was not delaying of recovering

Table 4

Correlations between knee kinematics-kinetics and knee muscle strength.

		ACL-M (n = 10)		ACL-F (n = 11)	
		Maximal torque of knee extension (% Nm/kg)	Maximal torque of knee flexion (% Nm/kg)	Maximal torque of knee extension (% Nm/kg)	Maximal torque of knee flexion (% Nm/kg)
Peak knee flexion angle (degree)	6 months postsurgery	$r = 0.248$ $P = 0.489$	$r = -0.006$ $P = 0.987$	$r = 0.482$ $P = 0.133$	$r = 0.609$ $P = 0.047$
	12 months postsurgery	$r = -0.745$ $P = 0.013$	$r = -0.578$ $P = 0.082$	$r = 0.718$ $P = 0.013$	$r = 0.679$ $P = 0.022$
Internal knee extension moment (Nm/kg)	6 months postsurgery	$r = 0.830$ $P = 0.003$	$r = 0.685$ $P = 0.029$	$r = 0.655$ $P = 0.029$	$r = 0.309$ $P = 0.355$
	12 months postsurgery	$r = 0.345$ $P = 0.328$	$r = -0.127$ $P = 0.728$	$r = 0.791$ $P = 0.004$	$r = 0.807$ $P = 0.003$

P values in bold type are significant.

quadriceps strength, however it did not contribute to recover knee biomechanics in this study. These results indicate that recovery of running biomechanics by 12 months postsurgery requires not only restoration of quadriceps strength.

There was a significant correlation between knee muscle strength and internal knee extension moments in both males and females 6 months following surgery, indicating that strengthening the knee extension muscle is necessary for the recovery of running movement. Xergia et al.²² showed significant correlations between the limb symmetry index of the single-limb hop distance and maximal knee extension torque at 180 deg/s in patients 6–9 months following ACL reconstruction, indicating that knee extension muscles could be correlated with motion biomechanics and performance 6 months postsurgery. In our female patients, kinematics and kinetic values were significantly correlated with the maximum torque values for flexion and extension at 12 months postsurgery, whereas only a negative relationship between the peak knee flexion angle and maximum torque of knee extension was measured in our male patients. Usually, activation of the quadriceps and lower hamstrings during running is greater in females.²³ Thus, female patients may rely more on knee muscle strength for running 12 months postsurgery, when the strength of their quadriceps and hamstrings reaches approximately >80% of the uninjured side.

This study has several limitations. First, our sample size was small, and we only analyzed sagittal plane biomechanics because of the investigative correlation with knee muscle strength. Second, this was a case-control study and did not follow the long-term implications of ACL surgery. The most important complications following ACL reconstruction are graft failure, with failure rates of 2.80% for bone-tendon-bone autografts and 2.84% for hamstring allografts,²⁴ and subsequent ACL injury. Our study used kinematics and kinetics data for running only and did not show whether enable to return to specific sports activities: however, running is necessary for most sports activity. Patients who have non-adequate biomechanics for running cannot return to sports, as this may cause a second ACL injury. We recruited the patients who underwent not only ACL reconstructed but ACL augmentation, and there was significantly difference in reconstructive surgery between male and female group. Therefore, it is limitation that no unify the operative methods.

Conclusion

At 6 months after ACL reconstruction surgery, the knee kinetics of patients during running are not fully recovered compared to healthy controls, although increasing knee muscle strength could contribute to the recovery of these abnormal movements both male and female. We recommend that individuals do not return to sports until after 6 months postsurgery because knee kinematics and kinetics involved in running take 6–12 months to recover, and promote the exercise of knee muscle strength for recovery these kinetics at 6 months after ACL reconstruction, especially female patients could keep the exercises at 12 months postoperative.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.asmart.2018.11.004>.

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