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The relationship between quadriceps strength asymmetry and knee biomechanics asymmetry during walking in individuals with anterior cruciate ligament reconstruction

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ABSTRACT

Background: Lower extremity movement asymmetries may lead to re-injury and knee osteoarthritis after anterior cruciate ligament (ACL) reconstruction surgery. However, there is no consensus regarding the effect of quadriceps strength asymmetry on lower extremity movement asymmetry after ACL reconstruction.
Research question: What is the relationship between quadriceps strength asymmetry and asymmetries in lower extremity kinematics and kinetics during walking in individuals who underwent ACL reconstruction surgery?.
Methods: Isometric quadriceps strength, kinematic, and kinetic data during walking were collected from 24 men with unilateral ACL reconstruction. Knee joint angles and moments were reduced. Pearson correlation coefficients between asymmetry in selected knee biomechanics and isometric quadriceps strength asymmetry were determined.
Results: The isometric quadriceps strength of the injured leg was significantly lower than that of the uninjured leg ($P < 0.001$). Knee flexion angles and knee extension moments were smaller in the injured leg than that in the uninjured leg during both loading response ($P = 0.007$, $P = 0.047$) and mid-stance phases ($P = 0.005$, $P = 0.028$). Isometric quadriceps strength asymmetry was significantly correlated with asymmetry in the peak knee flexion angle during loading response and mid-stance phases ($r = -0.48$, $P = 0.017$, $r = -0.48$, $P = 0.017$). Isometric quadriceps strength asymmetry was also significantly correlated with asymmetry in the peak knee extension moment during the mid-stance phase ($r = -0.44$, $P = 0.033$).
Significance: Individuals with ACL reconstruction demonstrate knee movement asymmetry in the sagittal plane. Isometric quadriceps strength asymmetry is significantly correlated with asymmetry in knee flexion angles during the early stance phase and knee extension moments during the mid-stance phase. Rehabilitation programs should emphasise eccentric exercise to beneficially modify quadriceps neuromuscular control.

1. Introduction

Anterior cruciate ligament (ACL) reconstruction is a common surgical procedure to restore functional joint stability after an ACL injury [1]. Although ACL reconstruction surgery restores joint stability [2], there is a high incidence of ACL re-injury, with up to 12% of patients sustaining a subsequent ACL re-injury [3,4]. Furthermore, there is a risk of early development of knee osteoarthritis (OA) after ACL reconstruction. The prevalence of radiographic knee OA in patients with combined ACL and meniscal injuries at 10–15 years after ACL reconstruction is 80% [5].

Lower extremity movement asymmetries may contribute to re-injury and knee OA after ACL reconstruction [6–8]. Athletes with hip and knee biomechanical asymmetries at the time of return to their sport are at least 3 times more likely to have a second ACL injury within one year than are those without these asymmetries [7]. Asymmetrical lower extremity loading alters chondrocyte synthesis and catabolic activities, which could lead to structural articular cartilage damage and may accelerate the development of post-surgical knee OA [9–11].

Numerous studies have evaluated the effect of common musculoskeletal impairments after ACL reconstruction on lower extremity movement asymmetries. Some studies have reported that patients with

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high quadriceps strength symmetry demonstrate lower limb movement asymmetry and greater functional performance than those in patients with low quadriceps strength symmetry [12,13]. However, Roewer et al. reported asymmetric knee angles and moments after ACL reconstruction in participants with symmetrical quadriceps strength [14]. Additionally, Curran et al. reported that, although quadriceps strength improved after reconstruction, asymmetric knee biomechanical parameters still existed [15].

Discrepancies regarding the impact of quadriceps strength asymmetry may be primarily due to a lack of information on the relationships between quadriceps strength asymmetry and asymmetries in lower extremity biomechanics during walking. Previous studies on lower extremity movement asymmetries only compared lower extremity kinematics and kinetics between groups/conditions of high and low quadriceps strength symmetry [12,13,16,17]; these studies did not actually examine the relationships between quadriceps strength asymmetry and asymmetries in lower extremity kinematics and kinetics. The lack of an understanding of the relationships between quadriceps strength asymmetry and asymmetries in lower extremity kinematics and kinetics creates an obstacle to determining the appropriate rehabilitation programs after ACL reconstruction for the prevention of ACL re-injury and knee OA.

The purpose of this study was to examine (1) knee movement asymmetry during walking and (2) the relationship between knee movement asymmetry and isometric quadriceps strength asymmetry in individuals who underwent ACL reconstruction surgery. We hypothesized that there would be significant differences between injured and uninjured legs in terms of isometric quadriceps strength, knee angles, and moments during walking. We also hypothesized that knee sagittal kinematic asymmetries would be significantly correlated with quadriceps strength asymmetry. We further hypothesized that knee extension moment asymmetry would be significantly correlated with quadriceps strength asymmetry.

2. Methods

2.1. Participants

Twenty-four males who underwent unilateral ACL reconstruction using a hamstring tendon autograft 6–10 months before the study (age: 32 ± 8.2 years, height: 1.75 ± 0.07 m, weight: 84.9 ± 12.3 kg, post-reconstruction duration: 7.4 ± 1.3 months) volunteered to participate in this study. All participants had an isolated ACL injury, without other ligament and meniscus injuries that needed to be repaired with resection or sutures, moderate or severe articular cartilage damage to the patellofemoral and tibiofemoral joints, or other current orthopaedic injuries or disorders that were still affecting lower extremity movements. The mean International Knee Documentation Committee (IKDC) score was 67.4. The use of human participants in this study was approved by the Institutional Review Board of Peking University Third Hospital. All participants read and signed a written informed consent before data collection.

2.2. Data collection

Each participant was asked to wear a pair of black spandex shorts. Passive reflective markers were placed bilaterally at the anterior and posterior superior iliac spines, lateral thigh, lateral and medial femoral condyles, anterior superior and inferior shanks, lateral and medial malleoli, heel, and first and fifth metatarsophalangeals. All participants were instructed to walk barefoot. Participants were asked to perform three successful trials in which each foot stepped on force plates at a self-selected speed.

Three-dimensional (3-D) trajectories of the reflective markers were collected using an 8-camera motion capture system (VICON, Oxford, UK) at a sampling rate of 100 Hz. Ground-reaction force signals were synchronously collected by two embedded force plates (AMTI, Watertown, Massachusetts) at a sampling rate of 1000 Hz.

Quadriceps strength was evaluated after the walking trial. Quadriceps isometric strength was assessed using an isokinetic dynamometer (CON-TREX MJ; Germany) during a maximum voluntary isometric contraction. The participant was seated with knee flexed at 60°, which is the optimum knee angle for maximal torque production [18]. The lateral femoral condyle was aligned with the dynamometer axis, and the dynamometer resistance pad was secured to the anterior aspect of the distal shank. After correcting for leg weight, the participant was asked to perform submaximal practice to familiarize themselves with the testing apparatus. Subsequently, the participant was asked to conduct three recorded maximum-effort trials (5 s in duration, with 60 s of rest between trials) for each leg, using the uninjured leg first.

2.3. Data reduction

The raw 3-D trajectories of the reflective markers were filtered using a low-pass fourth-order Butterworth filter at an estimated optional cut-off frequency of 10 Hz. Kinematic and kinetic variables were calculated using Visual 3D software (C-Motion Inc., Germantown, Maryland, USA). Knee joint angles were calculated as Cardan angles of the tibial reference frame relative to the femur reference frame in an order of (1) flexion-extension (x-axis), (2) abduction-adduction (y-axis), and (3) internal rotation-external rotation (z-axis). Joint moments were calculated using an inverse dynamic approach and transferred onto the distal segment reference frame. Joint moments and quadriceps strength were normalized to the production of body weight and height.

Joint moments of each stance phase were normalized; the initial foot contact represented 0%, and the toe-off represented 100%. Joint angles of each gait cycle were normalized; one gait cycle was identified as the time from initial foot contact to the time that the same foot made the next initial contact.

The quadriceps strength index (QI) was calculated using

$$QI = \frac{Y_{injured\ leg}}{Y_{uninjured\ leg}} * 100\%$$

where $Y_{injured\ leg}$ and $Y_{uninjured\ leg}$ are the magnitudes of the quadriceps isometric strength of the injured leg and uninjured leg, respectively.

The inter-leg difference (ILD) and coefficient of multiple correlation (CMC) of the knee biomechanics between injured and uninjured legs were calculated to investigate side-to-side symmetry during walking. The ILD between the injured and uninjured legs was calculated for joint angles and moments using

$$ILD = Y_{uninjured\ leg} - Y_{injured\ leg}$$

where $Y_{uninjured\ leg}$ and $Y_{injured\ leg}$ are the magnitudes of a given joint angle or moment of the uninjured and injured legs, respectively.

The CMC value for the knee joint angle over a full gait cycle or knee joint moment over the walking stance phase was calculated using

$$\mathrm{CMC} = \sqrt{1 - \frac{\sum_{i=1}^{N}\sum_{t=0}^{T}(y_{it} - \bar{y}_t)^2 / N(T-1)}{\sum_{i=1}^{N}\sum_{t=0}^{T}(y_{it} - \bar{y})^2 / (NT-1)}}$$

where N is the number of datasets (N = 2 in this study, *i.e.*, the injured and uninjured legs), T is the total number of time intervals for a normalized gait cycle (T = 100 in this study), y_{it} is the magnitude of the signal at normalized gait cycle t in set i, $\bar{y}_t$ is the mean of the signals in N sets at normalized gait cycle t, and $\bar{y}$ is the grand mean of the T + 1 samples of the signals in N datasets. The estimated means, $\bar{y}_t$ and $\bar{y}$, were determined using

$$\bar{y}_t = \frac{\sum_{i=1}^{N} y_{it}}{N}$$

$$\bar{y} = \frac{\sum_{i=1}^{N}\sum_{t=0}^{T} y_{it}}{NT}$$

ILD was used to yield information regarding symmetry between the legs at specific time points. An ILD of 0 indicates perfect symmetry between the two legs. The CMC value was used to represent the similarity between the injured and uninjured legs in terms of the knee kinematics and kinetics over the entire walking phase, and it ranges in value from 0 (waveforms are dissimilar) to 1 (waveforms are similar). The examination of waveform symmetry may yield different information about movement symmetry than that provided by a simple leg symmetry index calculation [19].

Several phases of walking were analysed. The loading response phase, which is accompanied by an eccentric contraction of the quadriceps, comprised the double-support period between the initial contact and the opposite-leg toe-off. The mid-stance phase was the period of gait cycle between the opposite-leg toe-off and heel rise. The terminal stance phase lasted from heel rise to the opposite-leg initial contact.

2.4. Data analysis

Paired t-tests were performed to compare isometric quadriceps strength and knee kinematic and kinetic variables of interest between the injured and uninjured legs during walking. Correlation analyses were performed to determine the relationships between quadriceps strength asymmetry and (1) inter-leg differences in knee kinematics and kinetics and (2) the similarity between the injured and uninjured legs in terms of knee kinematics and kinetics over the entire walking phase. All statistical analyses were performed using SPSS version 16.0 (SPSS Inc., Chicago, IL, USA). A type I error rate less than or equal to 0.05 was considered statistically significant.

3. Results

The isometric quadriceps strength of the injured leg (0.94 ± 0.28 Nm/kg/m) was significantly smaller than that of the uninjured leg (1.26 ± 0.28 Nm/kg/m) (QI = 0.746) ($P < 0.001$).

The injured leg had significantly smaller peak knee flexion angle during loading response ($P = 0.007$) (Table 1) and mid-stance phases ($P = 0.005$) (Table 1), knee range of motion during mid-stance ($P < 0.001$) (Table 1) and terminal stance phases ($P < 0.001$) (Table 1), compared to those in the uninjured leg. The injured leg also had significantly smaller peak knee extension moment during loading response ($P = 0.047$) (Table 2) and mid-stance phases ($P = 0.028$) (Table 2), peak knee flexion moment during the terminal stance phase ($P < 0.001$) (Table 2), and peak knee external rotation moment during the terminal stance phase ($P = 0.003$) (Table 2), compared to those in the uninjured leg.

The QI was significantly correlated with the ILD of the peak knee flexion angle during loading response ($r = -0.48$, $P = 0.017$) (Table 3) and mid-stance phases ($r = -0.48$, $P = 0.017$) (Table 3). The QI was also significantly correlated with the ILD of the peak knee extension moment during the mid-stance phase ($r = -0.44$, $P = 0.033$) (Table 3). However, the QI was not significantly correlated with the ILD of the knee range of motion during mid-stance and terminal stance phases, peak knee extension moment during the loading response phase, peak knee flexion moment during the terminal stance phase, and peak external rotation moment during the terminal stance phase ($P \geq 0.066$) (Table 3). The CMC values for the knee joint angles and moments during walking were greater than 0.72 (Fig. 1). None of the CMC values were significantly correlated with quadriceps strength asymmetry ($P \geq 0.073$) (Table 3).

4. Discussion

The present study results provide new information regarding asymmetries in knee biomechanics during walking in individuals who underwent ACL reconstruction. Furthermore, each of our three hypotheses were at least partially supported, as discussed below.

4.1. Injured and uninjured legs differ in isometric quadriceps strength and knee angles and moments

The results of this study support our first hypothesis that there would be significant differences between injured and uninjured legs in isometric quadriceps strength, knee angles, and moments during walking. The decreased quadriceps strength is supported by Norte et al. who also observed large asymmetries in quadriceps volumes measured by magnetic resonance imaging in individuals after ACL reconstruction [20]. We observed a decreased peak knee flexion angle during loading response and mid-stance phases in the injured leg compared to that in the uninjured leg, which is consistent with the studies by White et al. [21] and Sigward et al. [22]. Decreased knee flexion angles during early stance phases suggest that the injured leg utilizes a stiffer strategy during walking after ACL reconstruction surgery compared to that in the uninjured leg [23]. Between 0° and 30° of knee flexion, the joint contact in the medial compartment can shift anteriorly with decreasing knee flexion angle [24]. The medial tibial cartilage in the anterior region is thinner than that in the weight-bearing region; therefore, even normal medial compartment load magnitude can induce high stresses in the anterior region of the cartilage [25]. Khandha et al. reported that patients with OA at 5 years after ACL reconstruction demonstrated a significantly lower peak knee flexion angle than patients without OA [26]. Pamukoff et al. investigated the association between sagittal plane knee mechanics during gait and resting femoral cartilage thickness from ultrasonography, and then reported that larger knee flexion angle was associated with thicker medial femoral condyles cartilage [27]. Thus, our results, combined with those from previous literature, suggest that a stiffening strategy and an altered loading pattern after ACL reconstruction may be a potential mechanism for knee joint degeneration progression [28].

Table 1
Selected knee kinematics (mean ± standard deviation) during walking and inter-leg difference (ILD) of uninjured and injured leg.

Variables (degrees)	uninjured leg	injured leg	ILD	*P* value
Peak knee flexion angle during loading response phase	17.1 ± 7.6	13.9 ± 6.5	3.0 ± 5.2	0.007*
Knee range of motion during loading response phase	12.0 ± 4.2	10.4 ± 4.2	1.5 ± 4.1	0.078
Peak knee adduction angle during loading response phase	1.1 ± 1.9	1.2 ± 2.0	−0.1 ± 1.9	0.777
Peak knee flexion angle during mid-stance phase	17.4 ± 7.5	14.0 ± 6.7	3.1 ± 5.3	0.005*
Knee range of motion during mid-stance phase	10.6 ± 4.1	6.9 ± 3.0	3.5 ± 3.7	< 0.001*
Peak knee adduction angle during mid-stance phase	1.1 ± 2.1	1.2 ± 2.3	−0.2 ± 2.0	0.753
Peak knee external rotation angle during mid-stance phase	4.6 ± 4.4	6.5 ± 4.5	−1.8 ± 4.8	0.084
Minimum knee flexion angle during terminal stance phase	5.4 ± 4.4	6.5 ± 5.1	−1.2 ± 4.1	0.220
Knee range of motion during terminal stance phase	7.5 ± 2.0	5.4 ± 2.0	2.0 ± 1.9	< 0.001*

Abbreviations: ILD, inter-leg difference.
* $P < 0.05$.

Table 2
Selected knee kinetics (mean ± standard deviation) during walking and inter-leg difference (ILD) of uninjured and injured leg.

Variables (Nm/kg/m)	uninjured leg	injured leg	ILD	*P* value
Peak knee extension moment during loading response phase	0.330 ± 0.138	0.277 ± 0.108	0.053 ± 0.121	0.047*
Peak knee adduction moment during loading response phase	0.099 ± 0.096	0.096 ± 0.077	0.003 ± 0.113	0.892
Peak knee abduction moment during loading response phase	0.210 ± 0.055	0.184 ± 0.045	0.026 ± 0.069	0.080
Peak knee internal rotation moment during loading response phase	0.088 ± 0.039	0.086 ± 0.060	0.001 ± 0.065	0.915
Peak knee extension moment during mid-stance phase	0.347 ± 0.135	0.295 ± 0.132	0.052 ± 0.102	0.028*
Peak knee abduction moment during mid-stance phase	0.226 ± 0.055	0.206 ± 0.053	0.020 ± 0.076	0.216
Peak knee internal rotation moment during mid-stance phase	0.089 ± 0.048	0.090 ± 0.066	−0.001 ± 0.071	0.923
Peak knee flexion moment during terminal stance phase	0.117 ± 0.074	0.030 ± 0.068	0.087 ± 0.081	< 0.001*
Peak knee abduction moment during terminal stance phase	0.206 ± 0.072	0.177 ± 0.072	0.029 ± 0.079	0.092
Peak knee external rotation moment during terminal stance phase	0.054 ± 0.030	0.016 ± 0.052	0.038 ± 0.054	0.003*

Abbreviations: ILD, inter-leg difference.
* P < 0.05.

The present study also provides evidence that altered gait mechanics after ACL reconstruction are mostly in the sagittal plane, which appears more relevant to knee loading and post-traumatic knee OA. We found significant differences in sagittal plane biomechanics between the injured and uninjured legs, while no difference was observed in frontal plane biomechanics. Consistent with this, a recent meta-analysis suggested that sagittal plane biomechanics, rather than the commonly reported knee adduction moment, are more relevant in patients at risk of early OA development [29]. In the present study, the injured leg demonstrated a smaller peak knee extension moment during the loading response phase than the uninjured leg. Schmitz et al. demonstrated that a larger peak knee extension moment is positively correlated with medial femoral cartilage thickness in healthy individuals [30]. Therefore, the observed lower knee flexion angle and knee extension moment in the injured leg, compared to those in the uninjured leg, may contribute to an early degeneration of knee articular cartilage. A better understanding of sagittal plane biomechanics is necessary for optimal post-surgery rehabilitation and to potentially prevent early onset and progression of knee OA after ACL reconstruction. Interventions, such as quadriceps strengthening and gait retraining, may assist in correcting gait asymmetries in patients after ACL reconstruction.

4.2. Knee sagittal kinematic asymmetries are correlated with quadriceps strength asymmetry

The results of the present study partially support our second hypothesis that knee sagittal kinematic asymmetries would be significantly correlated with quadriceps strength asymmetry. We found that a greater QI was associated with a lower ILD in the peak knee flexion angle during loading response and mid-stance phases, but no correlation was found between the CMC values of the knee angle in the sagittal plane and the QI. A previous study demonstrated that patients with low quadriceps symmetry land with less symmetry in the knee flexion angle and knee extension moment than those with high and moderate quadriceps symmetry [13]. In addition, the association between weaker quadriceps strength and greater T1ρ relaxation times suggests that deficits in quadriceps strength may be related to early femoral cartilage degradation after ACL reconstruction [31]. Maximizing quadriceps strength early, *i.e.*, in the first 6 months after ACL reconstruction, may be critical for promoting cartilage health. Capin et al. also reported that athletes who sustained a second injury tended to walk with larger and more symmetrical peak knee flexion angles and less co-contraction [32]. A neuromuscular training program could significantly improve knee sagittal plane biomechanical measures in athletes with ACL reconstruction [33]. Therefore, the present results may further indicate that quadriceps strength asymmetry can affect asymmetry in specific variables during specific phases but may not be great enough to affect the symmetry of the entire gait cycle. Perhaps other factors, such as neuromuscular control and psychological factors, together contribute to lower extremity movement asymmetries.

4.3. Knee extension moment asymmetry is correlated with quadriceps strength asymmetry

The results of the present study also partially support our hypothesis that knee extension moment asymmetry would be significantly correlated with quadriceps strength asymmetry. In the present study, the ILD of the knee extension moment during the mid-stance phase was significantly correlated with the QI, while no significant association was observed between the ILD of the knee extension moment during the loading response phase and the QI. These results may be due to different contraction patterns and functions of the quadriceps during

Table 3
Pearson correlation coefficients between quadriceps strength symmetry and asymmetry of knee kinematics and kinetics.

			r	p value
ILD	Knee angle	Peak knee flexion angle during loading response phase	−0.484	0.017*
		Peak knee flexion angle during mid-stance phase	−0.483	0.017*
		Knee range of motion during mid-stance phase	−0.381	0.066
		Knee range of motion during terminal stance phase	0.143	0.504
	Knee moment	Peak knee extension moment during loading response phase	−0.354	0.090
		Peak knee extension moment during mid-stance phase	−0.436	0.033*
		Peak knee flexion moment during terminal stance phase	−0.366	0.078
		Peak knee external rotation moment during terminal stance phase	0.087	0.687
CMC	Knee angle	Knee angles in sagittal plane	0.373	0.073
		Knee angles in frontal plane	0.085	0.694
		Knee angles in transverse plane	0.283	0.181
	Knee moment	Knee moments in sagittal plane	0.119	0.578
		Knee moments in frontal plane	0.282	0.182
		Knee moments in transverse plane	−0.281	0.184

Abbreviations: ILD, inter-leg difference; CMC, coefficient of multiple correlation.
* P < 0.05.

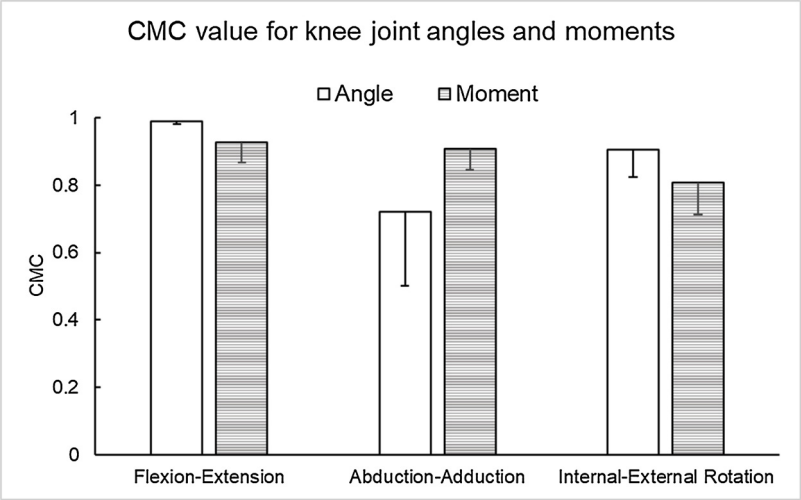

Fig. 1. The mean coefficients of multiple correlation (CMC) for knee joint angles and moments during walking.

different gait phases. The loading response phase is accompanied by an eccentric contraction of the quadriceps to limit the speed and magnitude of knee flexion. During the mid-stance phase, the quadriceps act concentrically to initiate knee extension [34]. Eccentric contractions exhibit unique neural strategies compared to those in concentric contractions, both under maximal and submaximal conditions [35]. Alterations in neuromuscular control that lead to injury may not be restored by conventional injury prevention/rehabilitation programs, which often target muscle strength. Recently published studies attempted to develop novel eccentric exercise protocols to optimize neuromuscular function in injury prevention and rehabilitation protocols [36]. To beneficially modify quadriceps neuromuscular control, eccentric exercise should be emphasized in future rehabilitation programs.

The results of the present study also suggest that quadriceps weakness is not the sole cause of deficits in knee extension moment. The observed reduced knee extension moment could represent a reduction in quadriceps activation, or an increase in flexor activity provided by the hamstring or gastrocnemius, especially during the loading response phase, which is accompanied by knee flexion. Although the quadriceps femoris is the primary dynamic stabilizer of the knee and plays a crucial role in decelerating knee flexion and absorbing shock when one lands on the lower extremity, asymmetries in knee movement patterns that occur during exercise are not simply due to low quadriceps strength. Oiestad et al. [37] reported that individuals with low self-reported knee function 2 years postoperatively and a loss of quadriceps strength between the 2-year and 10- to 15-year follow-up visits had a significantly higher risk of symptomatic, radiographically detected knee OA. However, quadriceps weakness after ACL reconstruction, by itself, was not significantly associated with knee OA. Therefore, rehabilitation therapists should not simply focus on isolated strengthening of a particular muscle; appropriate functional exercises aimed at improving neuromuscular control should be incorporated into rehabilitation programs to recover control and knee function.

4.4. Limitations

The present study has some limitations. Only male participants were included, which simplified the study design. Men and women may have different associations between gait asymmetries and quadriceps strength asymmetry after ACL reconstruction. Therefore, future studies are needed to evaluate these relationships in women who underwent ACL reconstruction. Another limitation is the lack of electromyographic data of muscles around the knee. Although asymmetries in knee flexion angles and knee extension moments during the early stance phase during walking have been found to be related to quadriceps strength asymmetry, this study has not yet determined the muscle contraction patterns and neuromuscular characteristics which may affect knee movement asymmetries. Further studies are needed to compare knee muscle contraction patterns to further clarify the mechanism that leads to the progression of knee joint degeneration after ACL reconstruction. Additionally, we only studied the biomechanics of the knee joint. Mechanisms affecting hip and ankle movements should be studied in the future to obtain a complete view of the mechanisms of movement asymmetries in patients who undergo ACL reconstruction.

4.5. Conclusions

Individuals after ACL reconstruction demonstrate knee movement asymmetries in the sagittal plane. Isometric quadriceps strength asymmetry is significantly correlated with asymmetry in knee flexion angle during the early stance phase and knee extension moment during the mid-stance phase. Rehabilitation programs after ACL reconstruction should emphasise eccentric exercise to beneficially modify quadriceps neuromuscular control.

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