Patellofemoral MRI Alterations Following Single Bundle ACL Reconstruction with Hamstring Autografts Are Associated with Quadriceps Femoris Atrophy*

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Summary: High incidence of patellofemoral pain and patellofemoral joint osteoarthritis was found following anterior cruciate ligament (ACL) reconstruction. The unstability of patellofemoral joint might be an important contribution factor. This study was designed to define the relationship between the unstability of patellofemoral joint and quadriceps femoris atrophy. Twenty patients underwent MRI scan before ACL reconstruction and every two weeks after surgery, until 12 weeks. The merchant's patellar congruence angle, lateral inclination angle, and quadriceps femoris muscle cross-sectional area were measured and the relationship between the changes of angles and the ratio of quadriceps femoris atrophy was studied by multiple regression analysis. Significant quadriceps femoris atrophy was observed after ACL reconstruction during the follow-up period of 12 weeks. The merchant's patellar congruence angle and lateral inclination angle significantly changed after surgery. The alterations of the merchant's patellar congruence angle were significantly correlated with the atrophy ratio of vastus medialis (coefficient=–15.76) and vastus lateralis (coefficient=8.35) during the follow-up period of 12 weeks. The alterations of lateral inclination angle were significantly correlated with the atrophy ratio of vastus medialis (coefficient=20.62), vastus lateralis (coefficient=–11.38) and rectus femoris (coefficient=–0.469) during the follow-up period 12 weeks. To sum up, ACL reconstruction can alleviate the dysfunction of patellofemoral joint to a certain extent. But, the unbalanced atrophy of quadriceps femoris once again destroyed the stability of patellofemoral joint following the operation, which might be one cause of patellofemoral joint pain and early onset of osteoarthritis after ACL reconstruction. So, rehabilitation training that focuses on quadriceps femoris especially the vastus medialis shortly following operation is suggested.
Key words: patellofemoral joint osteoarthritis; quadriceps femoris atrophy; joint instability; anterior cruciate ligament reconstruction

Anterior cruciate ligament (ACL) injury is one of the most frequent injuries associated with athletic activity, and ACL reconstruction (ACL-R) is a common procedure to re-establish knee stability and function[1]. However, the effectiveness of ACL-R in preventing osteoarthritis (OA) is still in controversy. Patellofemoral joint pain (PFP) is common after ACL-R[2, 3]. A relatively high incidence of OA, especially the patellofemoral joint OA (PFOA) after ACL-R is reported[4–7]. Significant tibiofemoral kinematics alterations have been recognized in knees with ACL failure which may contribute to OA[8, 9]. However, few studies have highlighted the patellofemoral kinematics alterations in patients after ACL-R.

Quadriceps femoris plays an important role in maintaining patellofemoral joint stability[10]. Strength weakness and quadriceps femoris atrophy are common in patients after ACL-R, which may affect patellofemoral joint[11]. However, the relationship between alterations of patellofemoral kinematics and quadriceps femoris atrophy is still unclear.

Muscle strength is generally measured by dynamometry method. Imbalance of the medial (vastus medialis) and lateral (vastus lateralis) force may affect patellofemoral kinematics, which may result in PFOA[12]. However, it is technique incapable of evaluating the separate contribution of a specific quadriceps subregion. Magnetic resonance imaging

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(MRI) is one technique capable of measuring muscle cross-sectional area (CSA) and such measurement is gaining popularity as a surrogate measurement to evaluate individual vasti muscle strength[13, 14]. In this study, we tried to define the relationship between alterations of patellofemoral kinematics and quadriceps femoris atrophy through MRI observation of the muscle CSA and patellofemoral kinematics. The results of our research offer a new idea to clarify the high incidence of patellofemoral pain and patellofemoral joint OA after ACL-R. Early targeted training that focuses on quadriceps femoris atrophy especially the vastus medialis after surgery is strongly suggested to reduce the complication.

1 MATERIALS AND METHODS

1.1 Patients

Twenty patients (11 males and 9 females; mean age: 26.1 years old) with ACL rupture were subjected to ACL-R in Fukushima Medical University School of Medicine between 2003 and 2004. The Ethics Committees of Fukushima Medical University (Fukushima, Japan) approved the study protocol, and all procedures performed in studies involving human participants were in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards also. All patients signed the informed consent.

1.2 Operative Technique

The same group of doctors performed the surgeries in Fukushima Medical University School of Medicine. Gracilis and semitendinosus from the ipsilateral side were harvested as autografts, and single bundle ACL-R was performed. The femoral tunnel was prepared by trans-tibial tunnel procedure, and grafts were fixed by TRANSFIX and INTRAFIX© fastener (DepuyMitek, USA).

1.3 Rehabilitation Training Project

After surgery, all the patients took the same rehabilitation training project. In the first week after surgery, knee joint was fixed in extensional position and isometric training was taken. From week 2 to week 4 postoperation, patients were given knee flexion and straighten to achieve joint motion of 0°–120°. Open Kinetic Chain was introduced to patients from week 4 postoperation. From week 6 postoperation, level walking and stair activity were suggested and the basis was still the Open Kinetic Chain. And from week 12 postoperation, patients could return to mild physical exercise such as jogging and fixed bicycle riding.

1.4 MRI Examination

All the patients underwent MRI scan before ACL-R and every two weeks after surgery, until 12 weeks. MR images of knees on a 1.5 Tesla MR scanner (General Electric Healthcare, USA) were obtained by a phase-array torso coil. The knees were flexed at about 30°. Sagittal T1-weighted spin echo (repetition time msec/echo time: 400–600/10–14 ms) or proton density-weighted fast-spin echo [2000–4000/30–40 (effective), echo train length=4] was obtained using an extremity coil, a 15 cm field of view, a matrix of 256×192, and a 4 mm slice thickness with 1 mm interslice gap.

Two independent observers performed all the evaluations of the MRI images. All the images were analyzed individually. They were all consultants in orthopaedic surgery and familiar with the MRI evaluation of the knee and the surrounding musculatures.

The merchant's patellar congruence angle, lateral inclination angle, and quadriceps femoris muscle cross-sectional area were measured by mimics 22.0 software (International Business Machines Corporation Company, USA). The merchant's patellar congruence angle and lateral inclination angle were measured on MRI images of knee joint on the first layer displaying femoral epicondylar axis from distal to proximal. Congruence angle is the angle between a line bisecting the sulcus angle and a line through the lowest point of the articular ridge of the patella and the vertex of the sulcus angle (fig. 1). Lateral patellofemoral angle is the angle between the line drawn across the most anterior aspect of the femoral condyles and the line along lateral patellar facet on axial imaging (fig. 2). The CSA of the quadriceps femoris was measured on 100 mm upper layer (fig. 3).

1.5 Statistical Analysis

Intraclass correlation coefficient was analyzed to evaluate intra- and inter-observer reliability of our measurement. All the indexes were shown as mean±standard deviation. Paired-samples *T* test was taken to analyze the difference of merchant's patellar congruence angle and lateral inclination angle preoperation and postoperation. Multiple linear

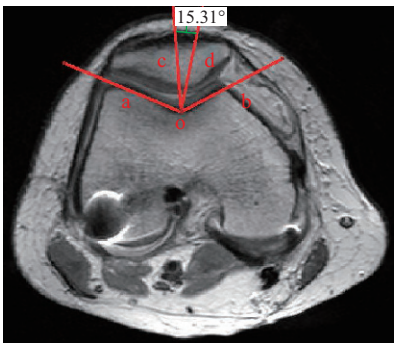

Fig. 1 Measurment of merchant's patellar congruence angle
Line C bisects the sulcus angle (∠AOB). Line B joins the vertex of the angle (∠AOB) to the lowest point of the patellar crest. The merchant's patellar congruence angle is the angle between line C and line D (∠COD). When line D is medial to line C, the merchant's patellar congruence angle is designed negative.

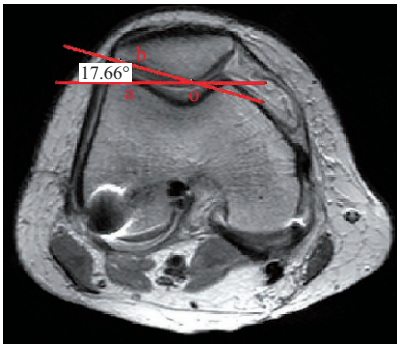

Fig. 2 Measurment of lateral inclination angle
Line A joins the anterior limits of the medial and lateral femoral condyles. Line B is tangential to the lateral facet of the patella. The lateral inclination angle is the angle between line A and line B (∠AOB). In the lateral of point O, lateral inclination angle was designed negative when line A is in front of line B.

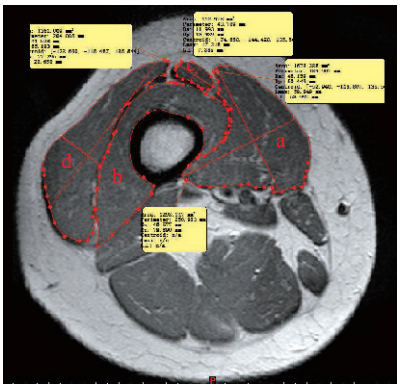

Fig. 3 Measurment of the quadriceps femoris CSA
The areas were manually circumscribed and then automatically calculated in the yellow box. Area A: vastus medialis; Area B: vastus intermedius; Area C: rectus femoris; Area D: vastus lateralis

regression analysis was used to analyze the relationship between merchant's patellar congruence angle, lateral inclination angle and the ratio of quadriceps femoris atrophy. SPSS Statistics 22.0 software (Inc., USA) was used for analysis. The results were considered significant at $P<0.05$.

2 RESULTS

2.1 Intra- and Inter-observer Reliability of Measurement

Table 1 shows the intra-observer reliability based on the two estimates of observer 1. The intra-observer reliability of the following 6 measurements was perfect for the all ICC valued >0.90 (table 1). Inter-observer reliability of our study is shown in table 2 based on estimates between observer 1 and observer 2. All the ICC valued >0.90 and it meant the measurements of excellent inter-observer reliability.

2.2 Effect of ACL-R on CSA of Quadriceps Femoris, Merchant's Patellar Congruence Angle and Lateral Inclination Angle

As shown in table 3, the CSA of each quadriceps femoris was not significantly different after ACL-R. The merchant's patellar congruence angle was 3.69±6.62° before surgery, which was significantly reduced after ACL-R (–3.59±6.01°). The mean value of lateral inclination angle before and after surgery was 6.81±6.19° and 12.61±5.40° respectively (table 3). Fig. 4 shows the typical contrast photographs before and after the surgery.

2.3 Measurements of Quadriceps Femoris, Merchant's Patellar Congruence Angle and Lateral Inclination Angle Every 2 Weeks During Follow-up Period of 12 Weeks

Fig. 5 shows the measurements of quadriceps femoris, merchant's patellar congruence angle and lateral inclination angle every two weeks during the follow-up period of 12 weeks. The CSA of quadriceps femoris was significantly less at the 12th week of the follow-up (fig. 5A–5D). The vastus medialis CSA reached the biggest atrophy ratio at 4th week after surgery, and then the CSA gradually increased with

Table 1 Intraobserver measurements

Variables	ICC	95% ICC	*P* value
Vastus medialis	0.984	(0.978, 0.988)	<0.05
Vastus intermedius	0.956	(0.941, 0.968)	<0.05
Rectus femoris	0.960	(0.945, 0.970)	<0.05
Vastus lateralis	0.978	(0.970, 0.984)	<0.05
Merchant's patellar congruence angle	0.984	(0.979, 0.988)	<0.05
Lateral inclination angle	0.985	(0.979, 0.989)	<0.05

Table 2 Interobserver measurements

Variables	ICC	95% ICC	*P* value
Vastus medialis	0.987	(0.982, 0.990)	<0.05
Vastus intermedius	0.970	(0.959, 0.978)	<0.05
Rectus femoris	0.963	(0.950, 0.973)	<0.05
Vastus lateralis	0.979	(0.971, 0.984)	<0.05
Merchant's patellar congruence angle	0.991	(0.988, 0.994)	<0.05
Lateral inclination angle	0.992	(0.989, 0.994)	<0.05

time (fig. 5A). However, the smallest CSA of vastus intermedius, rectus femoris and vastus lateralis was observed at 6th week after ACL-R (fig. 5B–5D). As shown in fig. 5E, the merchant's patellar congruence angle at 10th week of the follow-up was significantly higher than that at 2nd day after surgery and reached the biggest angle at 4th week after surgery. Interestingly, the mean value of merchant's patellar congruence angle after surgery was all negative (fig. 5E). A similar variation trend was found in lateral inclination angle (fig. 5F). And the two kinds of angle recovered at 12th week after surgery because there was no significant difference between the "0" group and the "12" group (fig. 5E and 5F).

2.4 Correlation between Alterations of Merchant's Patellar Congruence Angle, Lateral Inclination Angle and Atrophy Ratio of Quadriceps Femoris by Multiple Linear Regression

Significant correlation was observed between the alterations of the merchant's patellar congruence angle and the atrophy ratio of quadriceps femoris (R^2=0.407, P<0.05). As shown in table 4, the atrophy ratio of vastus medialis and vastus lateralis was significantly correlated with the alterations of the merchant's patellar congruence angle (P<0.05). The standardized coefficients of vastus medialis was –0.68 and the absolute value was larger than that of vastus lateralis (0.44). The data indicated that the atrophy ratio of vastus medialis might have more influence on the merchant's patellar congruence angle than the vastus lateralis (table 4). Another multiple linear regression also showed significant correlation between the alterations of lateral inclination angle and the atrophy ratio of quadriceps femoris (R^2=0.829, P<0.05). The atrophy ratio of quadriceps femoris except rectus femoris was found to be significantly corrected with the alterations of the lateral inclination angle (table 5). However, the standardized coefficient of rectus femoris was significantly less than that of vastus medialis and vastus lateralis (absolute value) (table 5) and the rectus femoris might have less impact on the lateral inclination angle. From table 4 and table 5, we can find that some coefficients were negative, which meant the angle increased with the increase in atrophy ratio of muscle, while the positive coefficients meant the angle reduced with the increase in atrophy ratio of muscle.

3 DISCUSSION

The postoperative complications (PFP and PFOA) took adverse effects on patients following ACL-R[15, 16]. It was reported that degeneration of

Table 3 The comparison of quadriceps femoris, merchant's patellar congruence angle and lateral inclination angle preoperation and postoperation

Variables	Preoperation	Postoperation	P value
Vastus medialis (cm^2)	1960.99±526.63	1953.63±530.73	0.135 (>0.05)
Vastus intermedius (cm^2)	1587.29±210.55	1578.58±220.50	0.090 (>0.05)
Rectus femoris (cm^2)	238.30±76.22	234.51±74.18	0.112 (>0.05)
Vastus lateralis (cm^2)	1711.75±353.46	1706.87±355.05	0.216 (>0.05)
Merchant's patellar congruence angle (°)	3.69±6.62	–3.59±6.01	3.63E-7 (<0.05)
Lateral inclination angle (°)	6.81±6.19	12.61±5.40	5.16E-6 (<0.05)

Table 4 Correlation between alterations of merchant's patellar congruence angle and atrophy ratio of quadriceps femoris by multiple linear regression (R^2=0.407, P<0.05)

Variables	Coefficients	95% CI	Standardized coefficients	P value
Vastus medialis	–15.76	(–19.56, –11.95)	–0.68	0.000 (<0.05)
Vastus intermedius	–1.90	(–6.83, 3.04)	–0.07	0.448 (>0.05)
Rectus femoris	1.32	(–1.42, 4.06)	0.09	0.342 (>0.05)
Vastus lateralis	8.35	(–6.83, 3.04)	0.44	0.000 (<0.05)

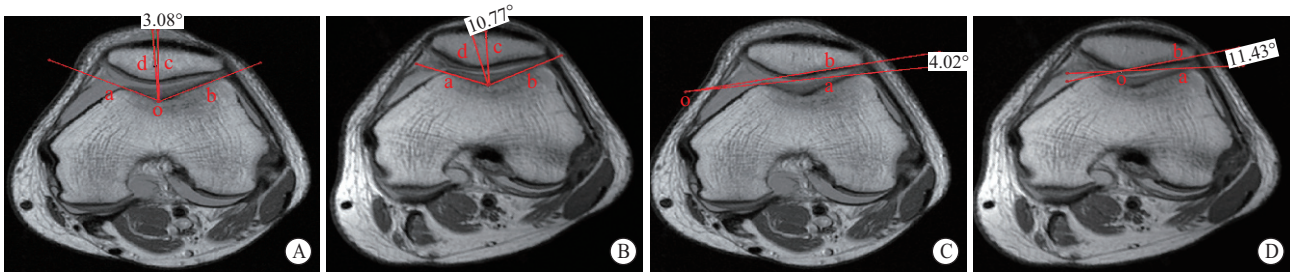

Fig. 4 The typical contrast photographs of merchant's patellar congruence angle and lateral inclination angle before and after the surgery
A: measurement of merchant's patellar congruence angle before surgery; B: measurement of merchant's patellar congruence angle after surgery; C: measurement of lateral inclination angle before surgery; D: measurement of lateral inclination angle after surgery

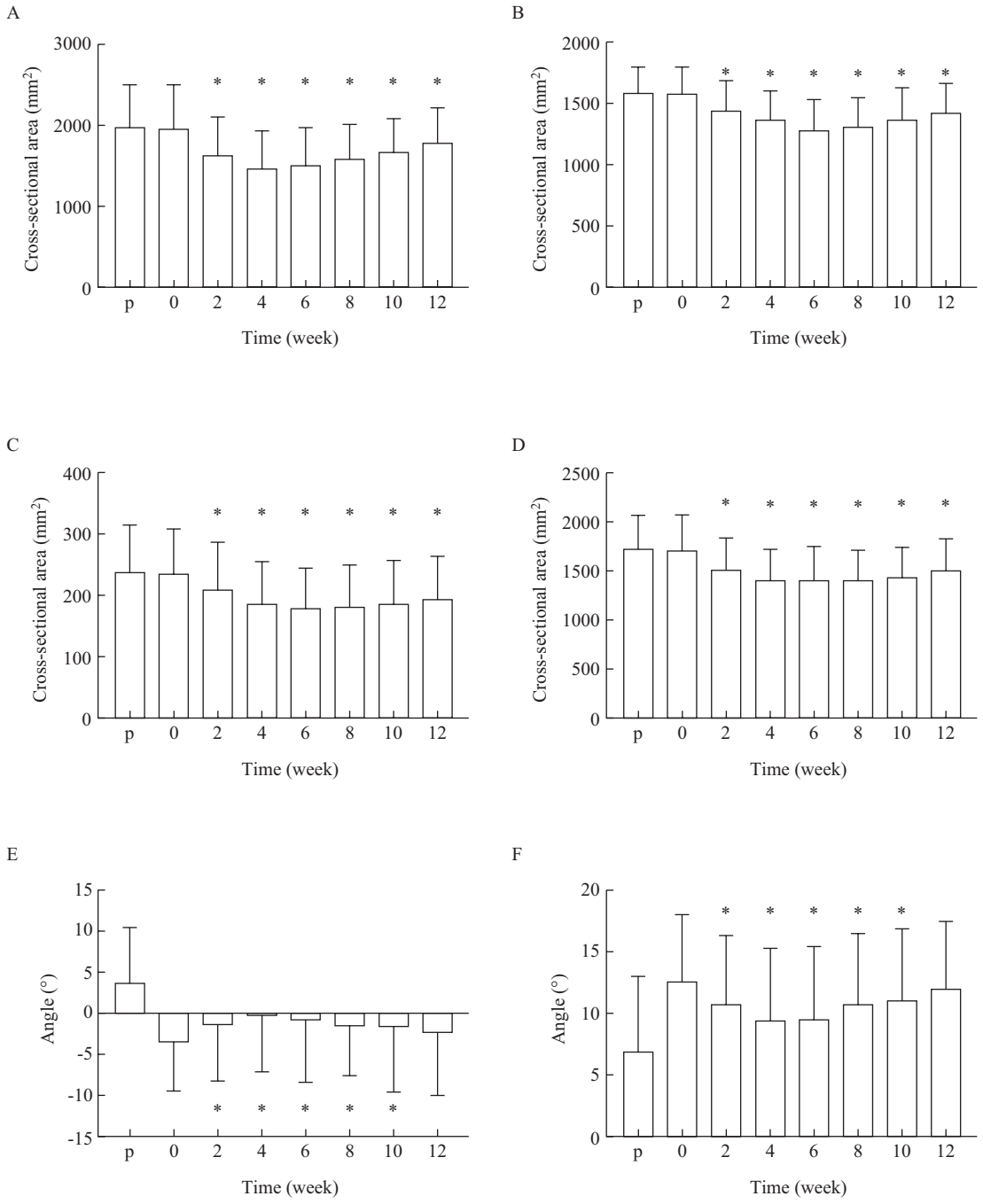

Fig. 5 Measurement results of quadriceps femoris, merchant's patellar congruence angle and lateral inclination angle every 2 weeks during follow-up period of 12 weeks

A: the CSA of vastus medialis; B: the CSA of vastus intermedius; C: the CSA of rectus femoris; D: the CSA of vastus lateralis; E: the merchant's patellar congruence angle; F: the lateral inclination angle. The "p" in abscissa means that the MRI was taken preoperatively and the other number means the time when the MRI was taken after surgery (the "0" means that the MRI was taken two days after surgery). The paired-samples *T* test was taken between the "0" group and the other groups. $^{*}P<0.05$

Table 5 Correlation between alterations of lateral inclination angle and trophy ratio of quadriceps femoris by multiple linear regression (R^2=0.829, P<0.05)

Variables	Coefficients	95% CI	Standardized coefficients	*P* value
Vastus medialis	20.62	(18.76, 22.45)	0.99	0.000 (<0.05)
Vastus intermedius	2.48	(0.09, 4.88)	0.10	0.042 (<0.05)
Rectus femoris	–0.47	(–1.80, 0.86)	–0.34	0.486 (>0.05)
Vastus lateralis	–11.38	(–13.29, –9.47)	–0.67	0.000 (<0.05)

patellofemoral articular cartilage in patients with ACL-R after 7–11 years was 30 times as high as that in normal controls by MRI observation[17]. Young ACL-R patients under 30 years old had earlier PFOA symptoms[18]. During a follow-up period of 12 years after ACL injury and reconstruction, the incidence of OA was similar to that of tibiofemoral OA, and they often co-existed. Since the early onset of PFOA is a common problem after ACL-R which impacts substantially activities of daily life and delays the time of returning to sports activities[6], enough attention should be paid to PFOA after ACL-R, and study of its pathogenesis is fundamental and essential to prevent its occurrence.

Several factors have been identified as contributors to secondary PFOA after ACL-R[3]. Accompanying meniscus injury was found to be more easily to develop into radiographic evidenced OA[19]. The graft selection of bone-patellar tendon-bone was also thought to increase the incidence of PFP and PFOA[20]. But no significant difference was found in the incidence of PFOA when compared to the hamstring graft use, and PFOA has been also problematic after ACL-R with hamstring graft[15]. Age, sex and body mass index might also have influence. However, the abnormal kinematics of the unstable patellofemoral joint might be the most important direct factor contributing to the patellofemoral joint cartilage degeneration after ACL-R[21].

In our study, we found that ACL-R can ameliorate the patellofemoral kinematics index but still has difference with the normal control, which was similar to that reported by de Vasconcelos[22]. The possible reason might be the single-bundle technique we have taken in the study which mostly resembles reconstruction of the anteromedial (AM) bundle of ACL. However, the posterolateral (PL) bundle of ACL is tense at 0°–30°of knee flexion to restore the rotational stability[23, 24]. So double-bundle technique is popular by many researchers with advantages of controlling rotational stability and reducing abnormal joint kinematics[25]. In Goro's research, double-bundle ACL-R better restored patellofemoral contact area and pressure than the single-bundle ACL-R method[26]. Nevertheless, some patients, treated with double-bundle technique, still had early signs of OA[7]. So, further study is needed to define the different influences on patellofemoral joint stability between single-bundle and double-bundle ACL-R.

The atrophy of quadriceps femoris might also play a pivotal role in keeping the normal anatomic relationship of patellofemoral joint. It was reported that the recovery of quadriceps strength has a strong relationship with satisfied outcome after ACL-R[27, 28]. In our study, we found abnormal involution of patellofemoral joint was associated with the unbalanced atrophy of quadriceps femoris, and it might be an important contributor to PFP and PFOA. Interestingly, some differences in degree of each specific muscle atrophy were observed and the duration and recovery time of atrophy were also different between the four separate muscles. But, even at 12th week after surgery, the CSA of the quadriceps femoris was still less than that preoperation. Such unbalanced atrophy of quadriceps femoris might have an effect on the patellofemoral kinematics alterations.

Congruence angle and lateral patellofemoral angle also changed with time in our study and the data revealed that the changes were related to the atrophy of vastus medialis and vastus lateralis. Congruence angle could reflect the relationship of the patellar articular ridge to intercondylar sulcus. It was reported the mean value of this angle was –6°±11°, and the lateral shift of patella relative to femoral trochlear would be larger when the angle increased[29]. The data of our research showed the angle was larger in the preoperative patient and reduced after ACL-R. During the follow-up period, the angle changed due to the muscles atrophy which might result in abnormal patellofemoral kinematics and PFP. Lateral patellofemoral angle reflects the inclination of patellar and the decrease in the angle results in patella tilting more laterally[30]. The inversion of this angle may occur when the patella laterally tilts seriously and the angle becomes negative[22]. Our study showed that the angle was larger after the ACL-R. However it changed during the follow-up period and is related to the atrophy of vastus medialis and vastus lateralis. The data revealed that the angle was the minimum at 4th week after surgery, which was significantly smaller than the first MRI observation after surgery. As a result, the patella may laterally tilt seriously, leading to abnormal stress in patellofemoral joint. In conclusion, the ACL-R can regain the above angle of patella orientation to a certain extent, and the unbalanced atrophy of quadriceps femoris nevertheless led to some bad changes in the angles which may cause significant changes to patellofemoral biomechanics and resulted in the PFP and PFOA.

Through the multiple linear regression analysis in our study, the regression correlation coefficient(β) of vastus medialis was found to be much larger than that of vastus lateralis. We suppose that might result from the angle between the muscles retract direction and the equilibrium direction of the patella and the inserts of vastus medialis in the distal upper third or upper half of the patella[31, 32]. It suggested that we should pay more attention to the rehabilitation training of vastus medialis. In some previously published studies, the vastus medialis was related to the incidence of PFP[33, 34]. According to the present results, severe atrophy of vastus medialis was observed as early as 4 weeks after surgery. So in the early weeks, more muscle rehabilitation protocol should be taken

to minimize the atrophy. What's more, at this time, no significant fatty degeneration of quadriceps femoris was observed, which was similar to the result reported by Magada's study[35]. It indicates that a good outcome of muscle rehabilitation exercise could be achieved in this period. Closed kinematic chain and selective vastus medialis oblique exercises such as functional electrical stimulation[36] might be strongly suggested in the immediate postoperative period according to our study.

There were still some limitations in our present study: (1) The indications of patellofemoral kinematics in our study were all static, not dynamic such as the patellar tracking. However, the data from our study still can reflect the stability and adaptability of patellofemoral joint[29, 30, 37]; (2) Muscle strength was not directly studied, though the decrease of muscle cross-sectional area is related with muscle weakness[13, 38]. More cases and further study are needed to be performed to clarify the relation between the patellofemoral alterations and quadriceps femoris atrophy; (3) A longer time follow-up time is needed.

To sum up, our work strongly suggests that ACL played an important role in maintaining patellofemoral joint stability and ACL-R can reduce the dysfunction of patellofemoral joint to a certain extent. However, during the early period following operation, the unbalanced atrophy of quadriceps femoris once again destroyed patellofemoral joint stability, which may be one cause of PFP and early onset of OA. Rehabilitation training that focuses on quadriceps femoris especially the vastus medialis after surgery is strongly suggested.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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