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Longitudinal Changes in Medial Meniscal Extrusion After ACL Injury and Reconstruction and Its Relationship With Cartilage Degeneration Assessed Using MRI-Based T1ρ and T2 Analysis

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Background: Anterior cruciate ligament (ACL) injury often leads to posttraumatic osteoarthritis (PTOA), despite ACL reconstruction (ACLR). Medial meniscal extrusion (MME) is implicated in PTOA progression but remains understudied after ACL injury and ACLR.

Hypothesis/Purpose: It was hypothesized that MME would increase longitudinally after ACL injury and ACLR, with greater changes in the ipsilateral knee compared with the contralateral knee, leading to cartilage degeneration. The study aimed to assess MME 3 years after ACLR and its relationship with magnetic resonance imaging (MRI) T1ρ and T2 as cartilage degeneration markers.

Study Design: Cohort study; Level of evidence, 2.

Methods: MME and relative percentage of extrusion (RPE) were measured on 3 coronal slices of 3-dimensional fast spin-echo images and the mean values were used. T1ρ and T2 sequences were obtained and cartilage compositional measurements were performed using in-house developed software with MATLAB. Mixed models were used to assess the longitudinal changes and linear regression was used to assess the relationships between RPE and T1ρ and T2 values.

Results: A total of 54 participants with unilateral ACL injuries underwent preoperative bilateral knee MRI. A total of 36 participants completed MR scans at 6 months and 3 years after ACLR. MME and RPE measurements demonstrated high reliability (ICC $>$ 0.88 and $>$ 0.91, respectively). The predicted values of MME and RPE from the mixed models showed that the ipsilateral side had significantly greater MME and RPE than the contralateral side at all 3 time points (P = .023 for MME; P = .013 for RPE at baseline; and $P < .001$ at 6 months and $P < .001$ at 3 years for both MME and RPE). The rate of change of MME and RPE on the ipsilateral side was significantly greater than that on the contralateral side ($P < .001$). Postoperative RPE was associated with T1ρ and T2 values in the posterior medial femoral condyle.

Conclusion: MME and RPE obtained pre- and postoperatively after ACLR on the ipsilateral side were significantly greater than those on the contralateral side, and the longitudinal increases on the ipsilateral side were greater than those on the contralateral side. Postoperative RPE was significantly associated with cartilage degeneration in the posterior medial femoral condyle.

Keywords: anterior cruciate ligament injury; anterior cruciate ligament reconstruction; medial meniscal extrusion; posttraumatic osteoarthritis; quantitative magnetic resonance imaging

Anterior cruciate ligament (ACL) injury has been associated with posttraumatic osteoarthritis (PTOA). While ACL reconstruction (ACLR) is a common treatment for knee instability after ACL injury, PTOA may still develop in the long-term postoperative period.[29] The risk factors for developing osteoarthritis (OA) in patients with ACL injury and ACLR are not yet fully understood. Medial meniscectomy is considered by some studies to be a significant risk factor for OA, particularly in the long-term follow-up.[3,7,17,29,32] The meniscus plays a crucial role in distributing the load to the cartilage.[23] It is important to note that

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loss of the load-distributing function of the meniscus can lead to OA progression, even without a meniscectomy. It has been reported that medial meniscal (MM) extrusion (MME) is an independent predictor of the development of tibiofemoral cartilage and subchondral bone lesions, as well as OA progression.[1,23,37,38,45] MM posterior root tear is well known as a common cause of MME.[4,14] MM root tears and extrusion were reported to play an important role in OA progression.[8,9] However, there are many cases with OA progression from increased MME even in the absence of MM posterior root tears, and the natural history of knee joint degeneration concerning MME is complex and not completely clarified. MME increases with meniscal tears, degeneration, elongation of the meniscotibial ligament (MTL), and osteophyte formation, which may indicate the early stage of OA.[13,23]

There are only a few reports on MME with ACL injury and ACLR. One study reported that longitudinal meniscal injuries are significantly affected MME and not improved by repair.[16] In ACLR without meniscal injury, MME has been reported to have a significant increase postoperatively.[14,33] Another study reported no difference in MME preoperatively compared with a control group of volunteers with healthy knees.[33] However, on the other hand, ACL-injured patients with concomitant MTL tears have been reported to have a higher incidence of MME.[30] Based on these findings to date, it is not clear whether MME is more prevalent in the ACL-injured knee compared with the contralateral knee, and longitudinal changes using more than 2 time points are also unknown. Therefore, it is not certain when MME occurs in patients who had ACLR and how long it continues to progress. The relationship between MME and magnetic resonance imaging (MRI) T1ρ and T2 values—a quantitative assessment of cartilage degeneration that has been established as an early factor in PTOA—has not been investigated but is needed.

We hypothesized that ACL-injured knees would already have greater MME than the contralateral knee, that MME would progress faster in the ipsilateral compared with the contralateral knee over time after ACLR, and that MME would be associated with T1ρ and T2 values of the cartilage. This study aimed to observe MME longitudinally from the time of ACL injury to 3 years after ACLR, to compare it with the contralateral side, and to assess the relationship between MME and cartilage degeneration.

METHODS

This prospective study was approved by our institutional review board. All participants were included by providing their consent forms for the study.

Patients

This cohort was recruited for the longitudinal evaluation of ACLR.[10,12,40-42,48] Patients with traumatic unilateral ACL injuries between July 2011 and September 2014 who had preoperative bilateral knee MRI imaging were included. Patients who were unable or unwilling to consent to the study, had a history of previous knee trauma, had previous knee surgery, required meniscus or cartilage repair, had a joint inflammatory disease, or had OA were excluded. The sample size for this study was calculated based on our preliminary T1ρ data. We expect to observe significantly higher T1ρ values in the medial compartments of injured knees compared to control knees, particularly in the most weight-bearing compartment (3 from the medial femoral condyles (MFC) and 1 from the medial tibia (MT)). The sample size required for each subcompartment to reach a power of 80% at a significance level of .05 was 12, 9, 34, and 11—the calculations of T1ρ quantification were adjusted for 4 multiple comparisons using a Bonferroni correction. We therefore proposed to study 50 adult patients with ACL injuries at baseline, allowing for up to 20% drop-out rate during the follow-up to ensure enough power for the study. The contralateral knees were supposed to be used as controls. Participants with missing preoperative, 6-month, and 3-year bilateral knee MRIs were also excluded.

Surgical Procedure

All ACLRs were performed by 1 of the 3 board-certified, fellowship-trained orthopaedic surgeons (C.B.M. and two other surgeons) at a single institution and were performed with an anatomic single-bundle ACLR with either hamstring tendon autografts or soft tissue allografts. Bone tunnels were drilled independently, with the femoral tunnel placed either through an anteromedial portal technique or an outside-in technique. All patients underwent the standardized postoperative rehabilitation protocol as previously described.[40]

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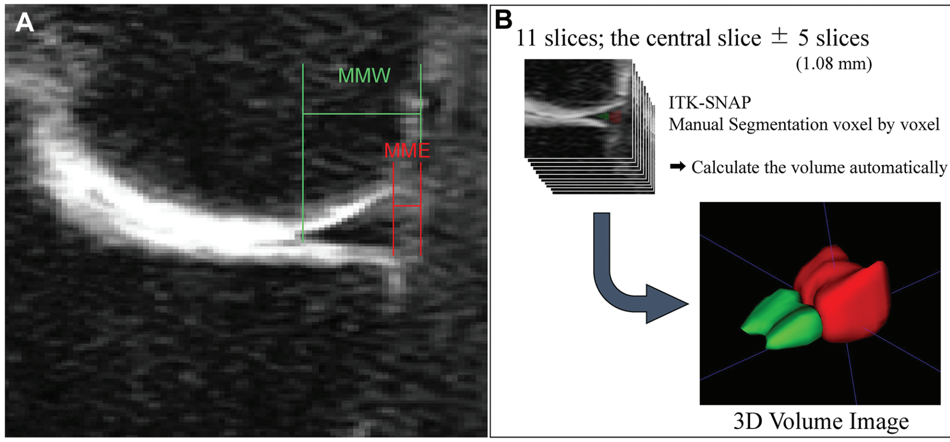

Figure 1. Measurement methods of MME and MM width. The coronal slice with the largest intercondylar ridge was defined as the central slice. (A) MME was defined as the length from the medial edge of the MM to the medial border of the tibia, excluding the osteophyte. The MMW was defined as the length of the entire MM from the medial edge of the MM to the central edge of the MM. (B) The 11 slices were annotated voxel by voxel for tibial MM (green) and MME (red). MM, medial meniscus; MME, medial meniscal extrusion; MMW, medial meniscal width; 3D, 3-dimensional.

Data Source

Patient characteristics—such as age, sex, height, weight, body mass index (BMI), and preoperative waiting period—were extracted from medical records, and surgical information was extracted from surgical records. The MRI data were stored in a secure system at our institution, from which the data were used for analysis.

MRI Acquisition

MRI was performed as previously described.[10,12,42] All images were performed using a 3.0 T MRI scanner (General Electric) with an 8-channel knee coil (Invivo Inc). The imaging protocol included sagittal high-resolution 3-dimensional (3D) fast spin-echo (FSE) images (repetition time (TR)/echo time (TE), 1,500/25 msec; echo train length, 32; matrix, 384 × 384; field of view, 16 cm; slice thickness, 1 mm [interpolated into 0.5 mm]) to evaluate cartilage and meniscal morphology, and a sagittal T1ρ/T2 quantification sequence developed previously in our laboratory[28] for assessing cartilage composition. The imaging parameters were as follows for T1ρ mapping: TR/TE, 8/3 msec; time of recovery, 1.2 sec; number of slices, 26; time of spin lock, 0/10/40/80 msec; spin-lock frequency, 500 Hz; field of view, 14 cm; matrix, 256 × 128; slice thickness, 4 mm; and views per segment, 64. The imaging parameters were as follows for T2 mapping: preparation TE = 0/13.7/27.3/54.7 msec; total acquisition time, 9 min 37 sec.

MME Measurement

MME measurements were performed on coronal reconstructions of the 3D-FSE images of both knees. First, we investigated the reproducibility and validity of the measurement method. The coronal slice with the largest intercondylar ridge was defined as the central slice, like that used in previous literature.[11,15,26] We further defined the central slice as the slice containing the lowest point of the femoral condyle, because the inter-slice distance in our images was 0.27 mm, smaller than that in most of the previous literature, which was often 3 mm. The MME and MM width were measured on 11 slices—including 5 slices anterior and 5 slices posterior to the central slice. MME was defined as the length (mm) from the medial edge of the MM to the medial border of the tibia, excluding osteophytes. The MM width was defined as the length (mm) of the entire MM from the medial edge of the MM to the central edge of the MM (Figure 1A). The relative percentage of extrusion (RPE) was defined as MME divided by MM width and multiplied by 100 as previously reported.[19] For further volume evaluation, the MM was segmented on those 11 slices, divided into MME and MM on the tibia, and the volume was measured on a voxel-by-voxel basis (Figure 1B). Each measurement was made with a software application named ITK-SNAP[47] in 10 knees and performed by 2 orthopaedic surgeons with >10 years of experience (S.W. and D.S.) who were not the operating surgeons of this study cohort. Symmetrical combinations were examined in the central slice only, 5 combinations of 3 slices, 1 combination of 5 slices, and all 11 slices. We investigated the reproducibility and the validity in the several combinations of slices. From these results, we chose 1 measurement method for measuring all MRI scans in this study, considering time efficiency. MME and MM width lengths were measured by 1 orthopaedic surgeon (S.W.) who was not one of the operating surgeons of this study cohort on all MRI scans of both knees at baseline (preoperatively), 6 months postoperatively, and 3 years postoperatively to calculate the RPE.

MRI Findings of Abnormalities in Knee Structures

All MRI examinations were evaluated in consensus by 1 radiologist with 15 years of experience (J.B.G.). The abnormalities included in the assessment were as follows: (1) ramp lesions, (2) lateral meniscus (LM) posterior root and other meniscus tears, (3) medial collateral ligament (MCL) injury, (4) posterolateral corner injury, and (5) MTL injury. An intrasubstantially situated complete thin, linear lesion between the posterior horn of the MM and the posteromedial capsule with an abnormally high fluid signal on fluid-sensitive sequences was defined as a ramp lesion on MRI (posterior medial meniscocapsular separation). Incomplete fluid interposition between the posterior horn of the MM and the capsule was also assessed. Ramp lesions were classified into 5 types using the classification of Thaunat et al[43]—type 1: meniscocapsular lesions; type 2: partial superior lesions; type 3: partial inferior or hidden lesions; type 4: complete tear in the red-red zone; and type 5: double tear. Meniscus root tears were defined as complete radial tears within 9 mm from the bony root attachment. MCL injuries were graded into 4 categories as follows: 0 = none; 1 = low grade; 2 = moderate grade; and 3 = high grade and rupture. Posterolateral corner injuries were graded into 4 categories as follows: 0 = none; 1 = low grade; 2 = moderate grade; and 3 = high grade and rupture. MTL injury was defined as abnormalities on MRI when there was a consensus that the ligament was poorly defined, attenuated, indistinct, or absent.[21,22]

Cartilage T1ρ and T2 Relaxation Times Quantification

The high-resolution 3D FSE images were downsampled in the sagittal direction and registered to the first echo of the T1ρ/T2 sequence. Postprocessing was done using in-house developed software with Matlab (Mathworks) integrated with the Elastix library for image registration.[20,39] Cartilage was segmented semi-automatically on 3D FSE images using an algorithm based on edge detection and Bezier splines,[5] MF, and MT. The MF was additionally subdivided into central medial femoral (cMF) and posterior medial femoral (pMF) subcompartments to examine the effects on each compartment of the knee (Figure 2). Registration was accomplished using an intensity-based multiresolution pyramidal approach and transferred from 3D FSE to the T1ρ and T2 maps pixel by pixel as previously described.[36] The mean T1ρ and T2 values were calculated for each cartilage compartment.

Statistical Analysis

Statistical analysis was performed using STATA Version 18 software (StataCorp LP). $P < .05$ was considered statistically significant.

We investigated the reproducibility in several combinations of slices by intraclass correlation coefficient (ICC) (1, 1) and ICC (2, 1), and the validity using the Spearman rank test with the RPE of MM volume.

Mixed models were used to assess the relationship between the joint side (predictor variable) and outcomes (MME and RPE of MM) over 36 months. These models included an interaction between the joint side and time point (baseline, 6 months, and 36 months) to explore how

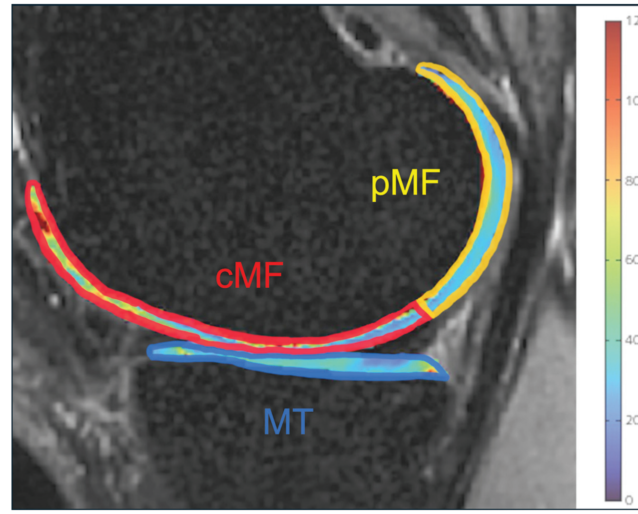

Figure 2. Segmentations of the MFC and tibial cartilage. MFC cartilage was subdivided into cMF (red area), pMF (yellow area), and MT (blue area) based on the meniscus. cMF, central medial femoral condyle; MFC, medial femoral condyle; MT, medial tibia; pMF, posterior medial femoral condyle.

changes differ between sides over time. The models accounted for repeated measurements for each knee and person while adjusting for BMI, age, and sex.

Before performing the primary analyses, we tested the models for nonlinearity and confirmed that the changes in measured variables over time were linear. In the final models, the beta coefficients represent the difference in how outcomes (MME and RPE of MM) change over time between the ipsilateral and contralateral sides (difference in slopes). In addition, these mixed models were used to compare outcomes between the ipsilateral and contralateral sides at each time point—baseline, 6 months, and 36 months.

As explorational analyses, we investigated the meniscus and knee structures and compared the RPE with or without each injury using the Welch *t* test.

The relationships between the RPE (independent variable) and T1ρ and T2 values (dependent variables) at 6 months and 3 years postoperatively were assessed using linear regression adjusted for BMI and age. The T1ρ and T2 values of cartilage variables were the values of cMF, pMF, and MT (Figure 2). The medial 3 compartments were chosen because the load occurs on cMF and MT during a standing position and on pMF and MT during knee flexion.

RESULTS

Patients Characteristics

A total of 54 patients were enrolled in this project, and 36 patients (16 women; 44%) completed the MRI scans at all 3 time points: baseline, 6 months postoperatively, and 3 years postoperatively. The mean age of the 36 patients at study enrollment was 31 ± 7.6 years, and their mean

TABLE 1
Baseline Characteristics[a]

Characteristics		
Sex	Male	20 (56)
	Female	16 (44)
Age, y		31 ± 7.6
BMI		23.9 ± 2.5
Side	Right	18 (50)
	Left	18 (50)
Time from injury to MRI, days		66.6 ± 49.2
Time from injury to surgery, days		82.3 ± 56
Graft	Hamstring tendon autograft	22 (61)
	Posterior tibialis allograft	13 (36)
	Hamstring tendon allograft	1 (3)

[a]Data are presented as mean ± SD or n (%). BMI, body mass index; MRI, magnetic resonance imaging.

BMI was 23.9 ± 2.5. A total of 22 patients (61%) received a hamstring tendon autograft, whereas the remaining patients received a soft tissue allograft. The mean time between initial injury and preoperative MRI was 66.6 ± 49.2 days. The mean time between initial injury and surgery was 82.3 ± 56 days (Table 1).

Measurement Method

Although the measurement using the 11 slices had the highest reproducibility, the measurement using the means of 3 slices also had sufficiently good reproducibility (Table 2). We decided to use the mean of 3 slices with central slice ± 4 slices (central slice ± 1.08 mm), which has a high ICC and a strong correlation with the volume measurement, considering time efficiency.

Meniscal Extrusion and RPE

The results of the actual observed MME and RPE of MM for the ipsilateral and contralateral side at each time point are shown in Table 3. The predicted values of MME and RPE of MM from the mixed models are also presented in Table 3. At all 3 time points, the ipsilateral side had significantly greater MME and the RPE of MM than the contralateral side (P = .023 for MME; P = .013 for RPE of MM at baseline; and P < .001 at 6 months postoperatively and P < .001 at 3 years postoperatively for both MME and RPE) (Table 3).

The mixed model shows that the rate of change of MME on the ipsilateral side is significantly greater than that of the contralateral side (coefficient, 0.013 [the difference in slope between the sides] [95% CI, 0.007-0.018]; P < .001) (Figure 3A). The mixed linear model also shows the rate of change of the RPE of MM on the ipsilateral side is significantly greater than that of the contralateral side (coefficient, 0.151 [95% CI, 0.082-0.219]; P < .001) (Figure 3B).

TABLE 2
The Reproducibility and Validity of the Measurement Method[a]

Measurement		ICC (1,1)	ICC (2,1)	Correlation With the Volume of Data
Volume data	MME	0.944	0.944	r = 1
	RPE	0.911	0.911	P < .000
Mean of 11 slices	MME	0.900	0.900	r = 0.990
	RPE	0.924	0.924	P < .001
Mean of 5 slices,	MME	0.846	0.845	r = 0.982
central ± 2, 4 slices	RPE	0.903	0.903	P < .001
Mean of 3 slices,	MME	0.859	0.858	r = 0.956
central ± 5 slices	RPE	0.907	0.906	P < .001
Mean of 3 slices,[b]	MME	0.885	0.884	r = 0.971
central ± 4 slices	RPE	0.917	0.916	P < .001
Mean of 3 slices,	MME	0.691	0.689	r = 0.977
central ± 3 slices	RPE	0.858	0.857	P < .001
Mean of 3 slices,	MME	0.720	0.719	r = 0.953
central ± 2 slices	RPE	0.847	0.846	P < .001
Mean of 3 slices,	MME	0.848	0.853	r = 0.965
central ± 1 slice	RPE	0.920	0.920	P < .001
Central slice	MME	0.721	0.733	r = 0.919
	RPE	0.852	0.852	P < .001

[a]Spearman coefficients are denoted by r. Significant probabilities are denoted by P. Central ± 3 slices means using 3 slices—including the central slice, the slice located at 3 slices after the central slice, and the slice located at 3 slices before the central slice. Central, the central medial femoral condyle; ICC, intraclass correlation coefficients; MME, medial meniscal extrusion; RPE, relative percentage of extrusion.
[b]We used this method for the analysis in this study.

MRI Findings of Abnormalities in Knee Structures

Ramp lesions with type ≥3 (regarded as unstable) were found in 12 knees (33.3%), LM posterior root tears in 7 (19.4%) knees, MM tears in 22 (61.1%) knees, and LM tears in 15 knees (41.7%). Posterolateral corner injuries with grades of ≥2 were observed in 14 (38.9%) knees, MCL injuries with grade 3 in 4 (11.1%) knees, and MTL injuries in 8 (22.2%) knees. The preoperative RPE of MM showed no significant differences between knees with and without injury (Table 4).

MME and Cartilage Degeneration Evaluated by MRI T1ρ and T2 Values

The RPE at 6 months postoperatively correlated positively with the T2 value in pMF at 6 months. The RPE at 3 years postoperatively also correlated positively with T1ρ and T2 values in pMF at 3 years (Table 5). No significant differences were observed in the other compartments.

DISCUSSION

The MME and RPE of MM preoperatively, 6 months postoperatively, and 3 years postoperatively were greater on

TABLE 3
MME and RPE[a]

	Ipsilateral Actual Value, Mean ± SD	Contralateral Actual Value, Mean ± SD	Ipsilateral Predicted Value (95% CI)	Contralateral Predicted Value (95% CI)	*P*
MME, mm					
Baseline	2.10 ± 0.37	1.99 ± 0.36	2.13 (2.01-2.24)	1.98 (1.86-2.10)	**.023**
6 months	2.25 ± 0.45	2 ± 0.29	2.21 (2.10-2.32)	1.99 (1.88-2.10)	**<.001**
3 years	2.62 ± 0.51	2.03 ± 0.46	2.63 (2.49-2.76)	2.03 (1.89-2.16)	**<.001**
RPE of MM, %					
Baseline	32.1 ± 6.4	30.1 ± 6.6	31.8 (30.1-33.6)	29.6 (27.8-31.4)	**.013**
6 months	32.8 ± 7.2	29.3 ± 5.5	33.0 (31.3-34.6)	29.8 (28.1-31.5)	**<.001**
3 years	38.5 ± 9.3	31 ± 7.9	38.5 (36.6-40.5)	30.9 (28.9-32.8)	**<.001**

[a]Each value is a predicted value from the mixed model and may differ from an actual observed value. The *P* values are calculated using a mixed model. Bold *P* values represent a significant difference ($P < .05$). Mixed models are adjusted for BMI, sex, and age.

BMI, body mass index; MM, medial meniscal; MME, medial meniscal extrusion; RPE, relative percentage of extrusion.

The mixed model shows that the rate of change of MME on the ipsilateral side is significantly greater than that of the contralateral side (coefficient, 0.013 [the difference in slope between the sides] [95% CI, 0.007-0.018]; $P < .001$,) (Figure 3A). The mixed linear model also shows the rate of change of the RPE of MM on the ipsilateral side is significantly greater than that of the contralateral side (coefficient, 0.151 [95% CI, 0.082-0.219]; $P < .001$) (Figure 3B).

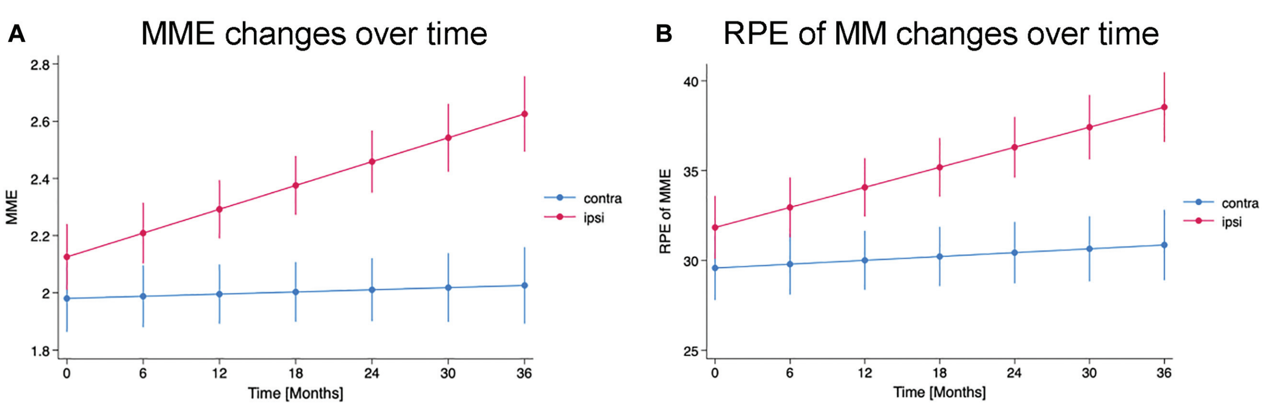

Figure 3. Changes in predicted MME and RPE of MM for each side over time. Time (from 0 to 36, in 6-unit increments) is plotted on the x-axis, while the predicted values of (A) MME and (B) RPE of MM are displayed on the y-axis. The predicted values are calculated based on a mixed-effects model, with 95% CIs shown on the graph. Each data point is a predicted value from the model and may differ from actual observed values. BMI, sex, and age are incorporated into the model as statistical adjustment factors. BMI, Body mass index; contra, contralateral; ipsi, ipsilateral; MM, medial meniscal; MME, medial meniscal extrusion; RPE, relative percentage of extrusion.

the ACL-injured knee than on the contralateral side and increased longitudinally from preoperatively to 3 years postoperatively. In a mixed-effect model that adjusted for age, sex, and BMI, the slope of the increase in MME and RPE was significantly greater for the ACL-injured knee than for the contralateral knee. Postoperative RPE of MM was significantly associated with T1ρ and T2 values of the cartilage in the pMFC.

In terms of the measurement method used in this study, the mean of 3 slices was used to improve the reproducibility of the measurement, and the ICC of the RPE of MM was higher than that of MME. Furthermore, this method showed a strong correlation with MME volume, indicating that it is useful as a measurement method. Most reports use the coronal slice with the largest intercondylar ridge or the coronal slice with the largest MME.[11,15,26] Jones et al[15] reported that the former provides a more accurate MME. However, many reports of both methods use images taken at a 3 mm interslice distance, which is hardly an accurate definition of the slices used.[11,26] Therefore, in the present study, we were able to improve reproducibility by using the lowest point of the medial condyle included in the slices with the largest intercondylar ridge. Some papers use MME measurements by volume.[18,34,46] However, it is difficult to generalize considering the time efficiency. In this study, we also evaluated the validity of the correlation with volumetric evaluation using 11 slices of the cMFC and searched for the best measurement

TABLE 4
RPE in Knees with and without Injuries on MRI Scans[a]

Injuries		n (%)	RPE, Mean (SD) With	RPE, Mean (SD) Without	*P*
Ramp lesion	None	20 (55.5)			
	Type 1	0			
	Type 2	4 (11.1)			
	Type 3	0			
	Type 4	12 (33.3)			
	Type 5	0			
Ramp lesion type ≥3		12 (33.3)	32.8 (2.3)	31.8 (1.2)	.70
MM tear		22 (61.1)	32.2 (1.5)	32.0 (1.4)	.94
LM posterior root tear		7 (19.4)	30.1 (2.1)	32.6 (1.2)	.33
LM tear		15 (41.7)	32.6 (1.6)	31.8 (1.5)	.73
MM or LM tear		29 (80.6)	32.8 (1.3)	29.3 (1.5)	.09
PLC injury	Grade 0	15 (41.7)			
	Grade 1	7 (19.4)			
	Grade 2	11 (30.6)			
	Grade 3	3 (8.3)			
PLC injury with grade ≥2		14 (38.9)	33.6 (1.7)	31.2 (1.4)	.27
MCL injury with grade 3		4 (11.1)	34.8 (4.2)	31.8 (1.1)	.53
MTL injury		8 (22.2)	35.6 (2.8)	31.1 (1.1)	.16

[a]Ramp lesions were classified into 5 types—type 1: meniscocapsular lesions; type 2: partial superior lesions; type 3: partial inferior or hidden lesions; type 4: complete tear in the red-red zone; and type 5: double tear. Posterolateral corner injuries were divided into 4 grades—0 = none; 1 = low grade; 2 = moderate grade; and 3 = high grade and rupture). MCL injuries were divided into 4 grades—0 = none; 1 = low grade; 2 = moderate grade; and 3 = high grade and rupture.

LM, lateral meniscus; MCL, medial collateral ligament; MM, medial meniscus; MTL, meniscotibial ligament; PLC, posterolateral corner; RPE, relative percentage of extrusion.

TABLE 5
Relationships Between the RPE of MM and the T1ρ and T2 Value in Cartilage Areas after ACLR[a]

Outcome Variables	RPE of MM	Coefficient	SD	*t*-Value	*P*
6 months postoperatively					
T2 in pMF	Constant	32.3	5.66	5.7	<.001
(R^2, 0.189)	RPE at 6 months	0.176	0.722	2.44	.021
3 years postoperatively					
T1ρ in pMF	Constant	47.54	5.09	9.34	<.001
(R^2, 0.21)	RPE at 3 years	0.111	0.511	2.17	.038
T2 in pMF	Constant	35.8	4.06	8.88	<.001
(R^2, 0.30)	RPE at 3 years	0.125	0.408	3.07	.004

[a]Regression analyses were performed with the T1ρ or T2 value of the area as outcome variables, and the RPE of MM, BMI, and age as independent variables. The RPE of MM had significant correlations only with pMF as shown above. pMF is defined in Figure 1 as pMF. No significant differences were observed in the other compartments. BMI, body mass index; MF, medial femoral; MME, medial meniscal extrusion; pMF, posterior medial femoral; RPE, relative percentage of extrusion.

method. The use of RPE could contribute to minimizing measurement error. We obtained higher reproducibility with RPE than with absolute MME.

Only a few studies on MME in ACLR have been reported. Katagiri et al[16] reported that longitudinal meniscal tears correlated with MME in ACLR and that meniscal extrusion persisted even after meniscal repair.[16] The present study examined MME in ACLR, excluding meniscal repair. A few other studies have reported MME after ACLR, excluding meniscal repair. Narazaki et al[33] reported greater MME in post-ACLR knees compared with normal knees in the control group. However, they reported no difference between normal knees and preoperative ACLR knees.[33] Hada et al[14] found MME (>3 mm) in 16.7% and 26.7% of patients before and after ACLR, respectively, and MME was greater postoperatively (7.6 months after ACLR) than preoperatively. Our study also showed similar results with the progression of MME, and this may continue for 3 years postoperatively. MME may be one of the most important risk factors for knee OA progression after ACLR without meniscal injury. The present study has another distinctive strong point in addition to the examination at 3 longitudinal time points up to 3 years later, which is the presence of the contralateral side MRI at each time point. Comparing the sides revealed that the MME of the ACL-injured knee was already greater than that of the healthy side at the time of pre-ACLR.

In our cases, we found no difference in RPE between knees with and without meniscal injuries, posterolateral corner injuries, MCL injuries with grade 3, and MTL injuries (Table 4). Krych et al[21] reported that MTL injury was involved in knees with large MME but no meniscal injury or knee trauma. These authors also reported that in patients with medial knee pain, the meniscus was extruded with its roots intact, resulting in a progressive tear of the posterior root.[22] The MTL is a critical stabilizing tissue and contributes to the stability of the meniscus.[35] Biomechanical studies have also reported that MTL insufficiency resulted in increased loading on the MM posterior root.[31] Mariani et al[30] reported that ACL-injured patients with concomitant MTL tears had a higher incidence of large MME (>3 mm). In our study, the preoperative MME was already greater in the ACL-injured knee than the contralateral side; however, there were no significant differences in preoperative MME with or without other injuries in ACL injuries knees—including MTL injury. Multiple analyses with large numbers of cases may be needed to detect the effects of the injuries on MME progression. Furthermore, it has been reported that preoperative intra-articular inflammatory biomarkers are linked to cartilage degeneration after injury.[25] Consequently, it may be also necessary to investigate the relationship between elevated MME and these biomarkers in a prospective study.

The T1ρ and T2 values of cartilage have been investigated in knees after ACLR and are useful for early detection of PTOA.[2,6,10,12,24,27,40-42,44,48] However, the cause of the prolonged T1ρ and T2 relaxation time of the cartilage is not completely known. Although MM resection is a known risk factor for OA after ACLR and cartilage damage after MM posterior root tear is also well known, it is important to note that there are no reports on the association between MME and cartilage degeneration using T1ρ and T2 values. In the present study, the association between RPE and T1ρ and T2 was investigated, and it was found that RPE was associated with cartilage degeneration. This finding is a significant contribution not only to the prediction of post-ACLR outcomes but also to the elucidation of progression of osteoarthritis.

The study has some limitations that should be considered. First, the number of cases analyzed was limited. However, it should be emphasized that the study still provides valuable and useful information because it analyzed ACLRs without meniscal repairs at 3 time points using MRI 3D FSE images, and cartilage T1ρ and T2 values were available. Second, the MRI images were not acquired under load. Nevertheless, it is important to acknowledge that the results of this study using these images are still meaningful, as most MRI scans used in clinical practice are unloaded. If weightbearing MRI were to become more widely used in clinical practice in the future, it may be worth considering weightbearing imaging in the study design. Third, the procedures were performed by 3 surgeons and with either autologous hamstring tendons or allografts, which may have influenced the data. In addition, this study only included results from the soft tissue ACLR technique, and there was no comparison to other graft types. Fourth, MRI was performed between the ACL injury and the reconstruction surgery, often about a week before the surgery, thus the time between injury and preoperative MRI scan was variable, potentially affecting the progression of MME during this time. Finally, there is uncertainty regarding whether MME increases more than 3 years after surgery, and it is unclear from this study whether there is an association between cartilage degeneration and OA in the future. While this study showed an association between MME and cartilage degeneration for the first time, it is important to conduct long-term follow-ups to gain a better understanding of the situation.

By excluding cases of meniscal repairs, it may be possible to obtain a more generalized effect of ACL injury and ACLR that can be accepted as fact. This study provided a basis for all future conversations regarding MME after ACLR. Future research should explore the causes of increased MME in ACL-injured knees, how to repair MME during reconstructive surgery, and whether subsequent MME progression can be prevented if repair can be achieved.

CONCLUSION

After ACLR, MME and RPE obtained preoperatively, 6 months, and 3 years postoperatively were significantly greater on the ipsilateral side than on the contralateral side, and the longitudinal increases on the ipsilateral side were greater than those on the contralateral side. The postoperative RPE of MM was significantly associated with T1ρ and T2 values of the cartilage in the pMFC. New insights have been gained into the progression of MME in patients undergoing ACLR and into the associations between cartilage T1ρ and T2 values and MME progression. These findings may be significant in understanding the development of OA after ACLR.

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