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Improvement in the medial meniscus posterior shift following anterior cruciate ligament reconstruction

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Abstract

Purpose Anterior cruciate ligament (ACL) reconstruction can reduce the risk of developing osteoarthritic knees. The goals of ACL reconstruction are to restore knee stability and reduce post-traumatic meniscal tears and cartilage degradation. A chronic ACL insufficiency frequently results in medial meniscus (MM) injury at the posterior segment. How ACL reconstruction can reduce the deformation of the MM posterior segment remains unclear. In this study, we evaluated the form of the MM posterior segment and anterior tibial translation before and after ACL reconstruction using open magnetic resonance imaging (MRI).

Methods Seventeen patients who underwent ACL reconstructions without MM injuries were included in this study. MM deformation was evaluated using open MRI before surgery and 3 months after surgery. We measured medial meniscal length (MML), medial meniscal height (MMH), medial meniscal posterior body width (MPBW), MM–femoral condyle contact width (M-FCW) and posterior tibiofemoral distance (PTFD) at knee flexion angles of 10° and 90°.

Results There were no significant pre- and postoperative differences during a flexion angle of 10°. At a flexion angle of 90°, MML decreased from 43.7 ± 4.5 to 41.4 ± 4.5 mm ($P < 0.001$), MMH from 7.5 ± 1.4 to 6.9 ± 1.4 mm ($P = 0.006$), MPBW from 13.1 ± 2.0 to 12.2 ± 1.9 mm ($P < 0.001$) and M-FCW from 10.0 ± 1.5 to 8.5 ± 1.5 mm ($P < 0.001$) after ACL reconstruction. The PTFD increased from 2.1 ± 2.8 to 2.7 ± 2.4 mm after ACL reconstruction ($P = 0.015$).

Conclusions ACL reconstruction affects the contact pattern between the MM posterior segment and medial femoral condyle and can reduce the deformation of the MM posterior segment in the knee-flexed position by reducing abnormal anterior tibial translation. It possibly prevents secondary injury to the MM posterior segment and cartilage that progresses to knee osteoarthritis.

Level of evidence IV.

Abbreviations

ACL	Anterior cruciate ligament
MM	Medial meniscus
MML	Medial meniscal length
MMH	Medial meniscal height
MPBW	Medial meniscal posterior body width
M-FCW	Medial meniscus–femoral condyle contact width
PTFD	Posterior tibiofemoral distance
OA	Osteoarthritis

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MRI   Magnetic resonance imaging
TR   Repetition time
TE   Echo time
ICC   Intraclass correlation coefficient

Introduction

In conservative treatment of anterior cruciate ligament (ACL) injuries, a high risk of meniscal injury or cartilage damage that progresses to knee osteoarthritis (OA) exists [1]. Long-term progression of knee OA still occurs even with ACL reconstruction [11]. However, studies have reported that patients who have undergone ACL reconstruction have a predominantly lower risk of developing OA than those who received conservative therapy for a knee with ACL failure [10, 15, 19]. This could be due to the increased injury in the medial meniscus (MM) in knees with chronic ACL failure [8]. Moreover, the MM surgery rate is reportedly six times higher in patients who undergo ACL reconstruction ≥ 12 months after an ACL injury [24], and a history of MM surgery associated with ACL reconstruction is a strong predictive factor for knee OA [12].

The ACL is a major source of resistance during the anterior drawer at all flexion angles and during internal rotation at flexion angles < 35° [20], while the MM is an important secondary stabilizer for anterior tibial translation [2, 13, 17, 23]. Abnormal anterior tibial translation moves the meniscal posterior segments posteriorly relative to the tibial surface [4], which is thought to be the mechanism involved in the increased incidence of MM tears observed in knees with chronic ACL injury [2]. ACL reconstruction seems necessary to prevent secondary MM injury. One magnetic resonance imaging (MRI) study by Narazaki et al. [18] reported that with 10° of knee flexion, the anteroposterior length and radial extrusion of the MM increased after ACL reconstruction; however, just how ACL reconstruction reduces MM injury remains unclear. In a previous radiograph study, ACL reconstruction suppressed abnormal anterior tibial translation [9]. The same was true for studies using cadaveric knees [14]. Therefore, it is suggested that ACL reconstruction can prevent sequential injury of the MM posterior segment during ACL insufficiency [8].

In this study, MM morphology and tibial position before and after ACL reconstruction were assessed using sagittal open MRI without weighting, at 10° and 90° of knee joint flexion. Furthermore, the influence of ACL reconstruction on the MM posterior segment was investigated. We hypothesized that ACL reconstruction affects the form of the MM and anterior tibial translation in ACL-injured knees. We also hypothesized that in knees with an ACL injury, abnormal anterior tibial translation results in excessive stress on the posterior segment of the MM during knee joint flexion and

that ACL reconstruction affects the contact pattern between the MM posterior segment and medial femoral condyle. This is because ACL reconstruction can reduce the deformation of the MM posterior segment by decreasing abnormal anterior tibial translation. Here the relationship between MM posterior segment and anterior tibial translation before and after ACL reconstruction was reported using open MRI.

Materials and methods

Between 2014 and 2016, 18 knees of 18 consecutive patients who underwent primary ACL reconstructions with intact MM were included in the study. In the final analysis, pre- and postoperative MRI scans of 17 knees (94%) were evaluated. One knee was excluded because of the lack of appropriate MRI scans. The patients (ten men and seven women) had a median age of 22 years (range 14–42 years). The median time from injury to preoperative MRI was 2 weeks (range 1–4 weeks). The median time at which the ACL reconstruction was performed was 3 months (range 1–5) after injury. Postoperative MRI was performed at a median of 3 months (range 3–4 months). Medical records were reviewed retrospectively to examine age, sex, height, body weight, Lysholm score [26], Tegner activity scale score [26] and MRI findings. Patient demographics are shown in Table 1.

Surgical procedure and postoperative care

Routine arthroscopic evaluation was performed prior to ACL reconstruction. No tears, instability and degenerative changes in the MM were observed during the surgery of any knees. All ACL reconstructions were performed using a hamstring tendon autograft (semitendinosus and/or gracilis muscles, anatomic double-bundle reconstruction). Femoral and tibial bone tunnels were created within the ACL

Table 1 Demographic and clinical characteristics

Variables	Number
Number of patients	17
Age, years (range)	22 (14–42)
Gender, male/female	10/7
Height, m (range)	1.66 (1.50–1.83)
Body weight, kg (range)	70 (55–97)
Interval from injury to surgery, months (range)	3 (1–5)
Concurrent lateral meniscus tear	6
Duration from surgery to postoperative MRI, months (range)	3 (3–4)
Follow-up period, months (range)	9 (3–12)

footprints as previously described [5, 6, 25]. Graft fixation on the femoral side was achieved using an Endobutton CL (Smith & Nephew, Andover, MA, USA) and ACL Tight-Rope (Arthrex, Naples, FL, USA). Graft fixation on the tibial side was performed using a double-spike plate and a screw (Meira, Aichi, Japan). An initial force of 30 and 20 N was applied to the graft for the anteromedial bundle and posterolateral bundle, respectively, at 10° of knee flexion. Postoperative rehabilitation protocols were similar for all patients. All patients began knee motion exercises and partial weight-bearing at 2 weeks postoperatively. Postoperatively, full weight-bearing and running were permitted at 1 and 5 months, respectively. Return to competitive sports was permitted at 8 months [6].

MRI measurement

MRI was performed using the Oasis 1.2 T (Hitachi Medical, Chiba, Japan) with a coil under the 10° and 90° knee-flexed position in a non-weight-bearing condition. Standard sequences of the Oasis included a sagittal proton density-weighted sequence (repetition time [TR]/echo time [TE], 1718/12) using a driven equilibrium pulse with a 90° flip angle and coronal T2-weighted multi-echo sequence (TR/TE, 4600/84) with a 90° flip angle. The slice thickness was 4 mm with a 0-mm gap. The field of view was 16 cm with an acquisition matrix size of 320 (phase) × 416 (frequency).

Measurements of the MM and tibial position were performed using a simple MRI-based meniscal sizing technique on the sagittal and coronal views at knee flexion angles of 10° and 90° (Figs. 1a, b, 2a, b) [7]. Details of the meniscal sizing are shown in Figs. 1 and 2. The axial views were taken parallel to the medial tibial plateau. A posterior condylar

(PC) line was drawn intersecting the most posterior edge of the femoral condyles on the axial image. The sagittal views were created vertical to the PC line. The measurement plane was a sagittal plane with the longest medial meniscal length (MML). Measurements at 90° of knee joint flexion were also performed using the same procedure. However, in consideration of the internal rotation of the tibia in the flexion position, the measurement plane was rotated 3 degrees internally from the PC line. In addition, in order to improve accuracy, the medial edge of the MM in the sagittal plane was determined as a reference in all cases. Furthermore, the number of slices every 4 mm of the measurement surface was the same before and after the surgery. The distance from the anterior to the posterior margin of the MM on the sagittal image was the MML (Figs. 1c, 2c). The medial meniscal height (MMH) was the distance from the bottom to the top of the MM posterior segment (Figs. 1c, 2c). The longest MML view was measured. The width of the inferior surface of the meniscus at its posterior segment was the medial meniscal posterior body width (MPBW) (Figs. 1c, 2c). The MM–femoral condyle contact width (M-FCW) was the distance from the inner edge of the MM posterior segment to the portion of contact between the upper surface of the MM posterior segment and the femoral condyle (Figs. 1c, 2c). The distance from the perpendicular line of the tibial posterior edge to the back of the femoral posterior condyle edge was the posterior tibiofemoral distance (PTFD) (Figs. 1c, 2c). To validate the measurements, four orthopaedic surgeons (HI, MF, YK and TO), who were blinded to the study aims, retrospectively reviewed the radiographic images and MRI scans. To determine intra- and interobserver repeatability, the intraclass correlation coefficient (ICC) was calculated based on two-way, random, single measures with
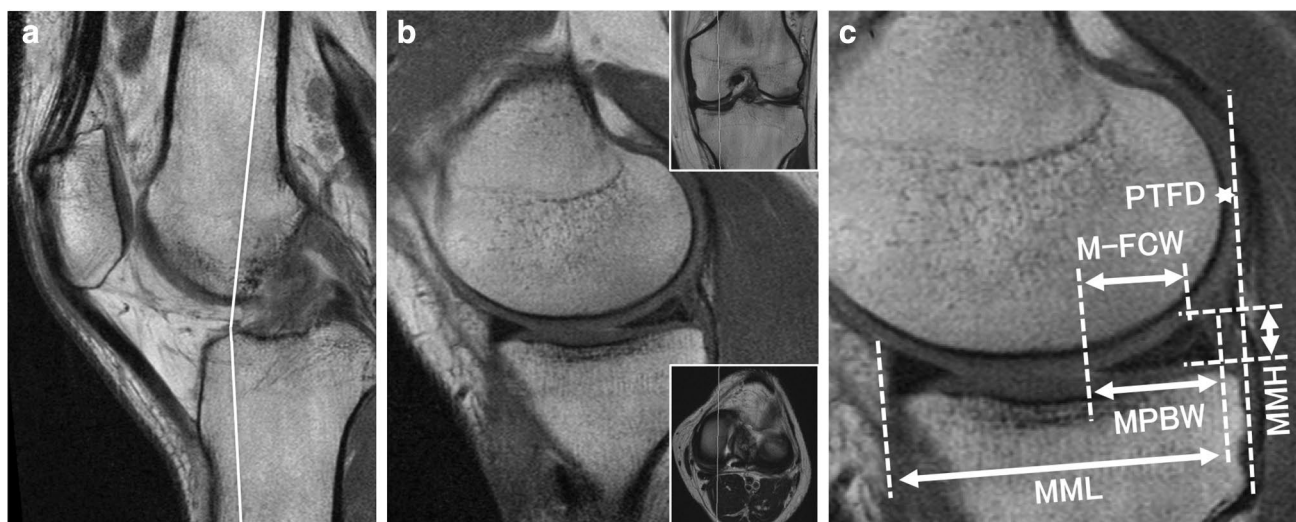

Fig. 1 MRI-based measurements. **a–c** Sagittal view of ACL-injured knee flexed at 10°. **b** Determination of measurement slice. **c** Measurement of MML, MMH, MPBW, M-FCW and PTFD
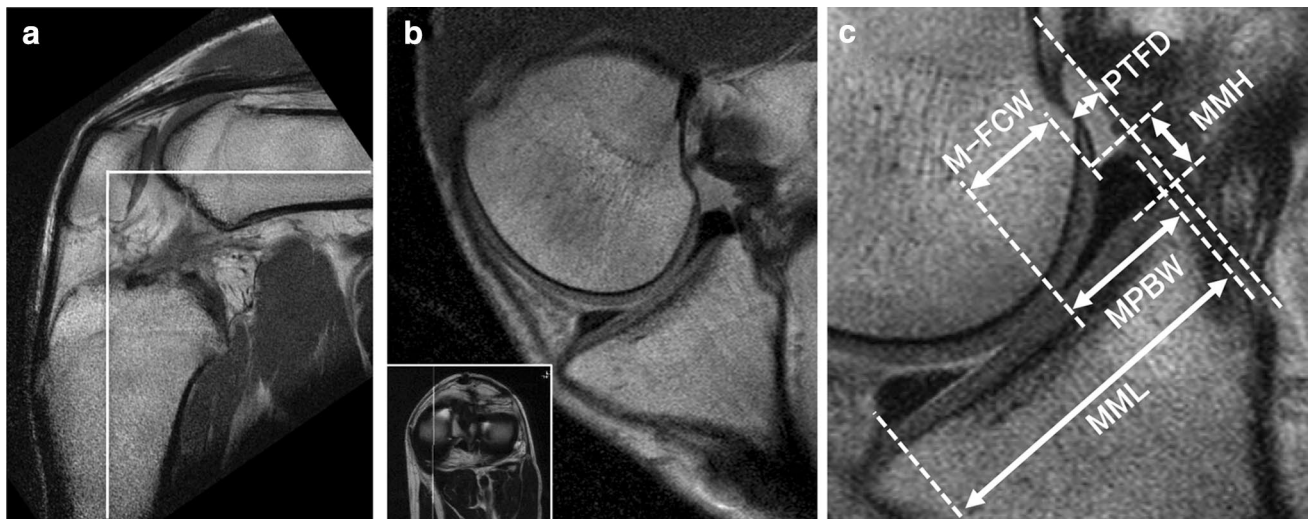
Fig. 2 MRI-based measurements. **a–c** Sagittal view of ACL-injured knee flexed at 90°. **b** Slice for meniscal measurement. **c** Measurement of MML, MMH, MPBW, M-FCW and PTFD at 90° of knee flexion

absolute agreement. All measurements demonstrated high precision with ICCs for both intra- and interobserver reliability levels of 0.92 or more. All parameters of the ACL-deficient (preoperative) and ACL-reconstructed (postoperative) knees were compared. The Lysholm score and Tegner activity scale score were used in the clinical evaluation.

This study was approved by Institutional Review Board of Okayama University Graduate School (1857), and the patients provided their informed consent.

Statistical analysis

Pre- and postoperative meniscal measurements were evaluated using the paired t test. Clinical value was evaluated using the Wilcoxon signed-rank test. Power and statistical analyses were performed using EZR-WIN software. Data are presented as the mean $\pm$ standard deviation. Significance was set at $P < 0.05$. Sample size was estimated for a minimal statistical power of 80% ($\alpha = 0.05$). All sample size and power calculations were completed using EZR-WIN software. Required sample size for the MPBW at 90° of knee flexion was 18.

Results

Clinical evaluations

ACL reconstruction improved knee-associated symptoms. Physical signs, such as knee joint swelling, joint-line tenderness or locking, were not observed during the final follow-up evaluation. Satisfactory clinical outcomes were noted postoperatively at a mean of 9 months (range 3–12 months). The

mean Lysholm score was 88.9 (range 77–95) before ACL reconstruction, which improved to 97.7 (range 93–100) at the final follow-up examination ($P = 0.004$). No significant difference was observed in the median Tegner activity scale score.

MRI-based measurement of the MM

Flexion angle of 10°

The MML decreased from 42.8 ± 3.7 to 42.5 ± 3.8 mm after ACL reconstruction (n.s.; Table 2). The MMH decreased from 5.7 ± 0.7 to 5.5 ± 0.7 mm (n.s.), the MPBW from 14.1 ± 2.0 to 13.9 ± 1.8 mm (n.s.), the M-FCW from 10.9 ± 2.0 to 10.2 ± 1.6 mm (n.s.) and the %M-FCW (M-FCW/MPBW $\times$ 100) from 78.0 ± 9.3 to $73.9 \pm 10.4\%$,

Table 2 Postoperative change in medial meniscal length (MML), medial meniscal height (MMH), medial meniscus posterior body width (MPBW), medial meniscus–femoral condyle contact width (M-FCW), M-FCW/MPBW $\times$ 100 and posterior tibiofemoral distance (PTFD) at a knee flexion angle of 10°

	Preoperative	Postoperative	P value
MML (mm)	42.8 ± 3.7	42.5 ± 3.8	n.s.
MMH (mm)	5.7 ± 0.7	5.5 ± 0.7	n.s.
MPBW (mm)	14.1 ± 2.0	13.9 ± 1.8	n.s.
M-FCW (mm)	10.9 ± 2.0	10.2 ± 1.6	n.s.
M-FCW/ MPBW $\times$ 100 (%)	78.0 ± 9.3	73.9 ± 10.4	n.s.
PTFD (mm)	3.7 ± 2.4	3.7 ± 1.4	n.s.

Data are displayed as a mean $\pm$ SD

Table 3 Postoperative change in medial meniscal length (MML), medial meniscal height (MMH), medial meniscus posterior body width (MPBW), medial meniscus–femoral condyle contact width (M-FCW), M-FCW/MPBW × 100 and posterior tibiofemoral distance (PTFD) at a knee flexion angle of 90°

	Preoperative	Postoperative	P value
MML (mm)	43.7 ± 4.5	41.4 ± 4.5	< 0.001*
MMH (mm)	7.5 ± 1.4	6.9 ± 1.4	0.006*
MPBW (mm)	13.1 ± 2.0	12.2 ± 1.9	< 0.001*
M-FCW (mm)	10.0 ± 1.5	8.5 ± 1.5	< 0.001*
M-FCW/ MPBW × 100 (%)	76.9 ± 8.7	69.5 ± 8.1	< 0.001*
PTFD (mm)	2.1 ± 2.8	2.7 ± 2.4	0.015*

Data are displayed as a mean ± SD

* Statistically significant

postoperatively (n.s.). The PTFD changed from 3.7 ± 2.4 to 3.7 ± 1.4 mm (n.s.). No significant differences were found.

Flexion angle of 90°

The MML decreased from 43.7 ± 4.5 to 41.4 ± 4.5 mm after ACL reconstruction ($P < 0.001$; Table 3). The MMH decreased from 7.5 ± 1.4 to 6.9 ± 1.4 mm ($P = 0.006$), the MPBW from 13.1 ± 2.0 to 12.2 ± 1.9 mm ($P < 0.001$), the M-FCW from 10.0 ± 1.5 to 8.5 ± 1.5 mm ($P < 0.001$) and the %M-FCW (M-FCW/MPBW × 100) from 76.9 ± 8.7 to 69.5 ± 8.1%, postoperatively ($P < 0.001$). The PTFD increased from 2.1 ± 2.8 to 2.7 ± 2.4 mm ($P = 0.015$). The differences were significant for all parameters.

At both 10° and 90° of knee flexion, the upper surface of the MM posterior segment was in contact with the medial posterior condyle of the femur preoperatively (Fig. 3a, b). At 10° of knee flexion, anterior tibial translation was unchanged
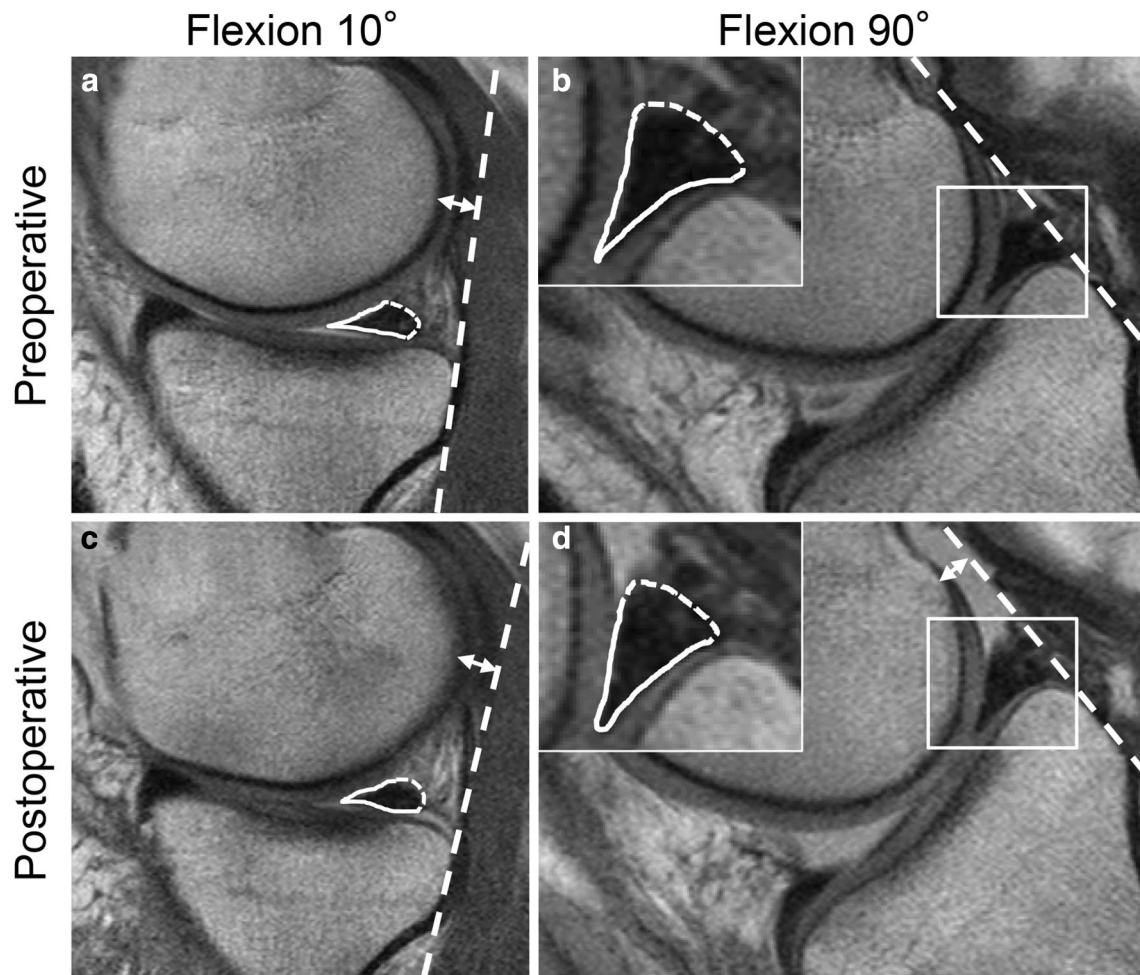

Fig. 3 Medial meniscal position on MRI. A 19-year-old woman with Judo-induced ACL injury. Preoperative sagittal images of the MM at knee flexion angles of 10° (**a**) and 90° (**b**). Postoperative sagittal images of the MM at knee flexion angles of 10° (**c**) and 90° (**d**). Inlets denote enlarged images of the MM posterior segment (**b**, **d**); dashed lines, posterior margins of the tibia; double-headed arrows, PTFD

after ACL reconstruction; similarly, not much change was observed in the morphology of the MM posterior segment (Fig. 3c). At 90° of knee flexion, however, ACL reconstruction reduced anterior tibial translation of the ACL-deficient knees. The PTFD was also reduced, and the compressed shape of the MM posterior segment showed improvement (Fig. 3d).

Discussion

The most important finding of the present study was that ACL reconstruction improved the anterior shifting of the tibia at 90° of knee flexion, suggesting the possibility that stress on the MM posterior segment was reduced. In knees with ACL failure, anterior tibial translation reportedly causes secondary injury to the posterior segment of the MM [2]. Thompson et al. and Yao et al. reported that movement of the meniscus backward during knee flexion is the least in the MM posterior segment [27, 29]. Moreover, compared with the extended position, in the deep flexion position of the knee joint, the contact area of the femoral tibial joint is reduced by 75% and the contact percentage between the meniscus and the femoral condyle is increased [29]. Allen et al. [2] reported that when a 134 N anterior load was applied to ACL-deficient knees, the resultant force on the MM increased by 52% in the full extension position and 197% at 60° flexion compared with healthy knees. Hence, the meniscus plays a vital role in load transmission

in a flexed position and the MM posterior segment is more susceptible to injury in knees with chronic ACL failure. In this study, the MM posterior segment morphology and anterior tibial translation position before and after ACL reconstruction showed no significant difference at 10° of knee flexion. On the other hand, at 90° of knee flexion, a more anterior position of the tibia, a greater surface area of contact between the MM posterior segment and the femoral condyle was observed, as well as a larger MM posterior segment before ACL reconstruction. These results show that in knees with ACL failure, the MM posterior segment is compressed to the medial femoral posterior condyle and shows posterior shifting due to abnormal anterior tibial translation at 90° of knee flexion, which in turn leads to the MM stretching in the posterior and superoinferior direction (Fig. 4a). A greater area of contact between the MM and the femoral condyle would reduce the contact pressure in the meniscus. However, we consider that an excessive contact pressure in the MM posterior segment at 90° of knee flexion may not be fully released by an increase in contact area between the MM and the femoral condyle in the ACL-deficient knee.

Meniscus-to-femoral condyle congruity is essential for the development of circumferential hoop stresses and meniscal function. Abnormalities in the position of the MM and its coverage, such as a meniscal root tear, substantial meniscal extrusion and meniscectomy-related meniscal defects, can alter knee joint congruity and are associated with the progression of tibiofemoral OA and cartilage degradation [3, 16, 22]. Thompson et al. [27] studied the anteroposterior
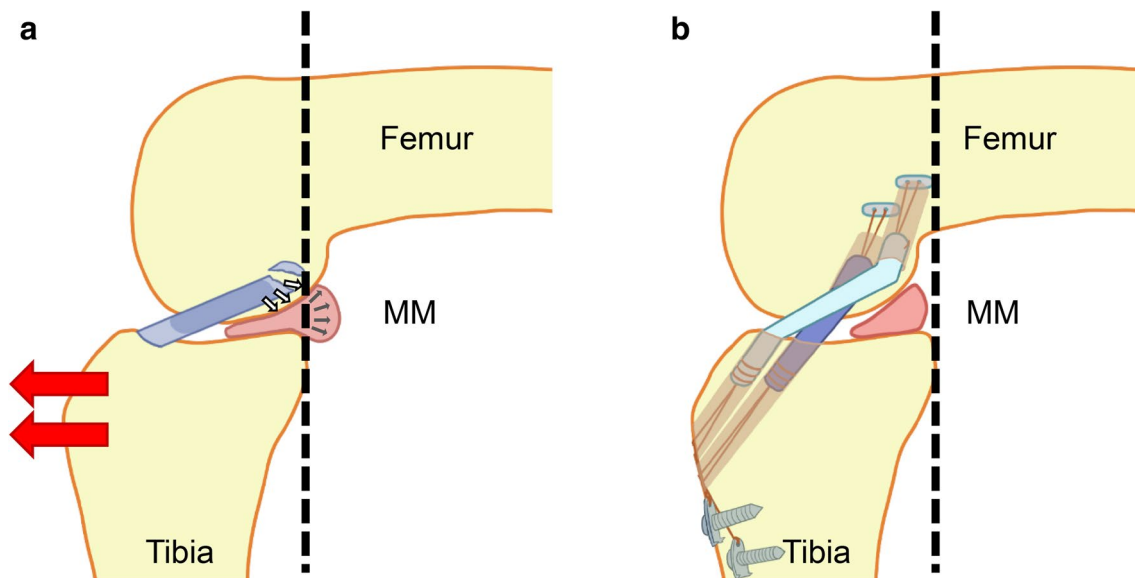

Fig. 4 Schematic illustrations of the MM posterior segment at 90° of knee flexion. **a** The ACL-deficient knee. The MM posterior segment compresses to the medial femoral condyle. Excessive anterior translation force to the tibia (red arrows). **b** The ACL-reconstructed knee.

The ACL reconstruction restores the positional relationship between the femur and tibia, and the compressed shape of the MM posterior segment is improved. Dashed lines denote the posterior tibial margins

translation of the anterior and posterior segments of the medial and lateral menisci captured with 1.5T MRI at 0° to 90° of flexion in five knees from fresh cadavers without weighting. They reported that the anterior and posterior segments of the MM had 7.0 and 3.2 mm of posterior shifting, respectively. Vedi et al. [28] used 0.5 T open MRI to study the dynamics of the anterior and posterior segments of the medial and lateral menisci in 16 footballers and reported that the anterior segment and posterior segments had 5.4 and 3.8 mm of posterior shifting, respectively, in a non-weighted position. In our study, the MML before ACL reconstruction increased by 0.9 mm, and after ACL reconstruction, it decreased by 1.1 mm from 10° to 90° of knee flexion. Thus, ACL reconstruction reduces deformation of the MM posterior segment and normalizes flexion-related MML changes by suppressing abnormal anterior tibial translation (Fig. 4a, b). Moreover, the morphology of the MM posterior segment in the flexion position of knees with ACL failure suggests increased contact pressure between the femoral condyle and the MM posterior segment, which may result in MM injury secondary to chronic ACL failure. On the other hand, it is considered that ACL reconstruction surgically removes excessive stress on the posterior segment of MM in knee-flexed position, thereby maintaining the structure and function of the MM and reducing the risk of developing knee OA. Surgeons should know that ACL reconstruction should not only improve knee instability, but also be a necessary treatment to protect MM.

This study had several limitations. The MRI-based medial meniscal size and tibial position were evaluated at knee flexion angles of 10° and 90° under non-weight-bearing conditions with a 4-mm slice thickness. Thus, a comparison of the real function of the MM in ACL-deficient and ACL-reconstructed knees using thin slices, at various knee flexion angles, and under a loading condition is necessary. Three-dimensional reconstruction of the MM using dynamic MRI may be useful to understand postoperative MM position and morphology changes. In this study, pre- and postoperative measurements were as similar as possible, but not necessarily identical. In addition, tears of the posterior horn of the MM may be underdiagnosed by intraoperative assessments that only use an anterolateral portal during ACL reconstruction [21].

Conclusions

In conclusion, this study, using open MRI, has shown that ACL reconstruction results in a decreased anterior tibial translation at 90° knee flexion and in the deference of MM morphology. ACL reconstruction possibly reduces the load on the MM posterior segment and prevents secondary injury to the MM posterior segment by suppressing anterior tibial translation at 90° knee flexion.

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