Medial meniscus posterior root repair restores the intra-articular volume of the medial meniscus by decreasing posteromedial extrusion at knee flexion.

Abstract

Purpose: Transtibial repair of a medial meniscus posterior root tear (MMPRT) can improve clinical outcomes, although meniscal extrusion remains. However, few studies have investigated the volume of meniscal extrusion. This study aimed to evaluate the effect of transtibial repair in reducing the volume using three-dimensional (3D) magnetic resonance imaging, at 10° and 90° knee flexion.

Methods: Twenty patients with MMPRTs and 16 volunteers with normal knees participated. The 3D models of meniscus were constructed using SYNAPSE VINCENT®. The meniscal extrusion and its volume were measured at 10˚ and 90˚ knee flexion. Differences between the pre- and postoperative examinations were assessed using the Wilcoxon signed-rank test. The postoperative parameters were compared to those in patients with normal knees.

Results: There were no significant pre- and postoperative differences in any parameter at 10° knee flexion. At 90° knee flexion, the posterior extrusion and its meniscal volume were decreased significantly after transtibial repair ($p < 0.05$), even though these parameters were larger than in the normal knees. On the other hand, intra-articular meniscal volume calculated by the extrusion volume was increased to the level of the normal knee.

Conclusions: This study demonstrated that transtibial repairs improved the intra-articular volume of the medial meniscus by reducing the posteromedial extrusion during knee flexion. This 3D analysis is clinically relevant in evaluating that, while transtibial root repair has a limited ability to reduce meniscal extrusion, it can restore the functional volume of the medial meniscus which contributes to the shock absorber postoperatively.

Level of Evidence: Level IV

Keywords: medial meniscus, posterior root tear, transtibial repair, meniscal volume, medial extrusion, three-dimensional magnetic resonance imaging.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
MME	Medial meniscus extrusion
MMEV	Medial meniscus extrusion volume
MMME	Medial meniscus medial extrusion
MMPE	Medial meniscus posterior extrusion
MMPRT	Medial meniscus posterior root tear
MMRV	Medial meniscus remaining volume
MMV	Medial meniscus volume

MRI	Magnetic resonance imaging

Introduction

Medial meniscus posterior root tear (MMPRT) is defined as a radial tear at the posterior attachment of the medial meniscus (MM) [1,23]. The root tear interrupts the continuity of circumferential fibres [21] and causes the progression of MM extrusion (MME) [10,30]. An open magnetic resonance imaging (MRI) study showed that the tear induced pathological meniscal translation beyond the posterior tibial edge at 90° knee flexion [26]. Substantial MME ≥ 3 mm is associated with meniscal degeneration, articular cartilage damage, and joint space narrowing [2,17]. Therefore, early diagnosis and appropriate treatment are important in preventing progressive osteoarthritis [13,30].

Unsatisfactory outcomes have resulted from conservative treatment and meniscectomy [19,20]. Several meniscal repair methods have been developed, including transtibial repair, anchor-dependent suture, and direct all-inside suture [7]. Of these, transtibial repairs demonstrated significant postoperative improvements in clinical scores [4]. However, many studies have reported that the root repair could not sufficiently reduce MME [14,16]. In fact, there is little MRI evidence to confirm the effectiveness of these repairs in the reduction of MME.

Conventional MRI might not assess the maximum MME as the measuring slice is often not parallel to the straight direction of extrusion from the tibial edge [12]. Thus, a three-dimensional (3D) MRI has been developed to measure the MME and the meniscal size [6,31,35,36]. Recently, the 3D volume analyser SYNAPSE VINCENT® (Fuji Medical System, Tokyo, Japan) has been shown to precisely estimate the volume of the meniscus [31]. MME volume is considered a comprehensive parameter of meniscal extrusion. However, it is unclear whether root repairs can reduce this volume.

This is the first study to compare meniscal volumes, including both extra- and intra-articular parts, in root-repaired and normal knees at 10° and 90° knee flexion. The purpose of this study was to evaluate postoperative changes of MME and meniscal volume after transtibial root repair. It was hypothesised that the root repair would decrease the volume of MME at knee flexion, while increasing the intra-articular volume to that of the normal knee. This 3D method is also useful for visualizing meniscal translation during knee flexion, and may demonstrate the contribution of surgical procedures to restoration of normal meniscal function.

Materials and methods

This study was approved by the Institutional Review Board of Okayama University Graduate School (ID number：1857) and written informed consent was obtained from all patients. From August 2017 to May 2019, 20 patients who underwent meniscal root repair, and 16 volunteers with normal (uninjured) knees were included. The normal group was matched to the patient group with respect to age, height, and body weight (Table 1). MMPRTs were diagnosed using the characteristic MRI findings of ghost/cleft/radial tear signs of the root, and the giraffe neck sign [3,9]. The surgical repair was indicated for patients with a femorotibial angle <180°, mild cartilage lesion (Outerbridge Grade I or II), and Kellgren–Lawrence Grade 0–II, which were confirmed with preoperative radiographs and

MRI. Types of root tear were confirmed by intraoperative examination according to the LaPrade classification as follows: Type 1 and 2 were partial and complete radial tears, respectively; Type 3 was a complete radial tear with a bucket-handle tear; Type 4 was an oblique tear into the root attachment; and Type 5 was a root avulsion fracture [23]. Types 2 and 4 tears were treated by transtibial repairs using either a modified Mason-Allen suture or a two simple stitches suture [8,27] (Fig. 1). After the appropriate tension (20-30 N) was applied by a spring tensioner, tibial fixation was performed using a double-spike plate or bioabsorbable screw.

Postoperatively, all patients were kept non-weight-bearing with a knee immobilizer for the first 2 weeks. After 2 weeks, knee flexion exercise was started, gradually progressing to 120° knee flexion at 6 weeks. Partial weight-bearing using crutches was increased by 20 kg per week, with progression to full weight-bearing at 6 weeks. Postoperative MRI examinations were performed 3 months after the surgery.

MRI acquisition and 3D reconstruction

The patients underwent open MRI examinations using the Oasis 1.2 T (Hitachi Medical, Chiba, Japan) while non-weight-bearing. Multiplanar images with continuous 1-mm slice thickness were taken in the 10° and 90° knee-flexed positions with the knee held in neutral rotation. Knee flexion angle was measured using a knee goniometer. Proton density-weighted isotropic resolution fast spin-echo (iso FSE, Hitachi Medical) sequence was applied in the sagittal and coronal planes with repetition time/echo time: 600/96 ms; matrix: 224×224; field of view: 18 cm; 1 average; echo-train length: 24; bandwidth: ±98.1 kHz; and scanning time: 4.8 min.

MRI images were transferred to the 3D image analysis workstation SYNAPSE VINCENT®. The 3D models of the femur and tibia were obtained semi-automatically by the volume-rendering technique [32], with an intensity threshold segmentation of the bone surfaces (Fig. 2a, d). The 3D model of the meniscus was extracted manually by a radiologic technologist using the texture tracing technique [35]. A previous study has already shown excellent agreement between the 3D reconstructed volume and the real meniscal volume [31]. Quality control of these segmentations was also performed by two expert readers (YoO, FT) with >5 years' experience in MRI analysis of the meniscus.

Measurement methods

In the 3D meniscus model, the MME area was defined as the outer region of the joint surface by identifying the tibial border and cutting the inner part of the meniscus [6]. A reference line was drawn passing through the tibial intercondylar eminences (Fig. 2b, e). The medial edges of the meniscus and tibia were determined by a line perpendicular to the reference line. The posterior edges of these were defined by drawing lines parallel to the reference line. MM medial extrusion (MMME) was measured as the distance from the tibial medial edge to the meniscal medial edge. MM posterior extrusion (MMPE) was defined as the distance from the tibial posterior edge to the meniscal posterior edge.

The volume calculation of the meniscus was accomplished automatically using the SYNAPSE VINCENT® via voxel counting. MM volume (MMV) was defined as the whole volume of the MM. MME volume (MMEV) was measured as the volume of the extruded portion of the meniscus (Fig. 2c, f). The MMEV ratio was calculated as MMEV divided by MMV to adjust for individual differences. The intra-articular volume was described as the MM remaining volume (MMRV), which was the MMEV subtracted from the MMV. The MMRV ratio (MMRV / MMV × 100) was also calculated. The above 3D parameters were compared between preoperative and postoperative values, at 10° and 90° knee flexion. In addition, the postoperative values were compared to the values in the normal group. These reliabilities were assessed using the intraclass correlation coefficient (ICC) with a 95% confidence interval (CI). A radiologic technologist and two surgeons (YoO and TF) retrospectively segmented the meniscal border to create the 3D meniscus in a blinded manner. The ICC was calculated for each MRI measurement using two-way, random, single measures with absolute agreement.

Statistical analysis

All statistical analyses were performed using SPSS Statistics Version 25.0 (IBM Corp., Armonk, NY, USA). The postoperative changes were examined using Wilcoxon signed-rank test. The Mann-Whitney *U*-test was used to compare the postoperative values of the MMPRT group to the normal groups. *P* values less than 0.05 were considered statistically significant. The sample size was estimated using a power of 80% and α of 0.05. The number of samples of MMPE, MMEV, and MMRV required for the statistical power were 9, 8, and 18, respectively.

Results

Postoperative changes in 3D parameters

Flexion angle of 10°

The transtibial repair reduced MMEV with decreasing MMME, but significant differences were not observed in all parameters (Table 2).

Flexion angle of 90°

Postoperative MMPE was significantly decreased, but there were no significant differences in MMME and MMV (Table 3). However, the MMEV and MMEV ratios were significantly decreased. In contrast, MMRV and MMRV ratios were increased postoperatively.

Comparison of the postoperative parameters with normal knees

At 10° of knee flexion, MMME, MMV, and MMEV were significantly greater in the patient group that underwent root repair than in normal group (Table 4). At 90° of knee flexion, MMME, MMPE, MMV, and MMEV were significantly greater in the patient group, while the MMRV did not differ significantly between the two groups.

Reliability evaluation

Inter-observer reliability

The ICCs of MMME and MMPE were 0.92 (95% CI 0.82–0.97) and 0.95 (95% CI 0.89–0.98), respectively. The ICCs of MMV and MMEV were 0.88 (95% CI 0.78–0.94) and 0.85 (95% CI 0.72–0.92), respectively.

Intra-observer reliability

The ICCs of MMME and MMPE were 0.92 (95% CI 0.79–0.97) and 0.91 (95% CI 0.77–0.97), respectively. The ICCs of MMV and MMEV were 0.89 (95% CI 0.79–0.94) and 0.83 (95% CI 0.69–0.92), respectively.

Discussion

The most important finding in this 3D analysis was that the transtibial repair for MMPRT reduced MMPE and MMEV at 90° knee flexion, even though these parameters were not improved to the level of a normal knee. In addition, the MMRV and MMRV ratios were increased after the surgery. These results suggest that the repair could control posterior translation of the meniscus during knee flexion, and restore meniscal function by increasing the intra-articular volume of the MM.

The meniscal posterior root acts as an anchor to the bone for restricting excessive meniscal translation, as well as supporting the function as a shock absorber in converting the axial load into hoop stress [1,7,33,34]. It has been shown that the shock absorption is approximately 20% less in the knee following a total meniscectomy [37]. MMPRT leads to a disruption of the posterior anchor, resulting in a biomechanical condition much like a total meniscectomy [1]. This present 3D reconstruction demonstrated that, during knee flexion, the extruded meniscus was moved in the posteromedial direction with increases of the MMPE and its thickness (Fig. 3a, b). A strength of this analysis is considered to be the quantification of the posteromedial extrusion by measuring MMEV.

Given the improvement of clinical outcomes after meniscal root repair, there are some unfavourable data regarding the ability to reduce MME on postoperative MRI [14]. Kim et al. reported that the transtibial repair decreased MME in 87% of patients, and the mean extrusion decreased to only 2.94 mm [16]. A comparative analysis on the use of one- and two-tunnel repair techniques found that neither method could reduce extrusion by less than 3 mm [24]. Similarly, significant reduction of MMME was not observed in this study (Fig. 3c). In contrast, a notable reduction of MMPE was found at 90° knee flexion (Fig. 3d). A recent biomechanical analysis by Daney et al. demonstrated that an anatomical repair could reduce the medial compartment contact pressure at knee flexion to that of an intact knee [5]. Thus, the decrease of MMPE and MMEV is associated with restoration of the posterior anchor and a reduction in the contact pressure.

The present study showed that transtibial repair increased MMRV. The meniscus optimizes its shape during knee flexion according to the articular congruence [11, 28]; the contact area increases and, as a result, the contact pressure on the articular surfaces decreases [15,22]. A biomechanical study found that MMPRT caused a significant decrease in the medial compartmental contact area (23%–44%

decrease) at 90° knee flexion, whereas the repair could restore the contact area to the level of an intact knee [34]. Thus, the postoperative increase of MMRV is associated with improvement of the contact area and pressure. A positive explanation is that the meniscal root repair has the effect of restoring the meniscal shock absorber function.

On the other hand, this study revealed that the sutures at the posterior horn could not reduce MMEs (MMME and MMPE) or MMEV to the normal level. Narrowing of the medial joint space is often combined with MMPRT [30]. It is conceivable that the extruded meniscus has already lost its flexibility due to swelling of the peripheral margin [31]. This fact might support the effectiveness of peripheral stabilization, such as with the centralisation technique using a suture anchor [18] and/or an additional suture/s to the posteromedial part of the meniscus [29]. In addition, it remains unclear how weight-bearing should be progressed after meniscal root repairs to prevent the risk of an increase in MME. Laprade et al. recommended no weight-bearing for the first 6 weeks to prevent impact stress on the repair, and then gradually progressing to full weight-bearing as tolerated without pain or swelling [25]. Thus, MMEs might have been decreased by delaying our protocol of weight-bearing.

There were several limitations to this study. First, the sample size was small because of the time-consuming task of performing MRIs and creating 3D reconstructions. Second, the measurements of MME and the meniscal volume were conducted without axial joint loading. Although it is difficult to reproduce full weight-bearing on MRI, a similar condition will be required to confirm the surgical contribution towards MME reduction. Third, the inter- and intra-reliability in our Vincent method was relatively low, which can be attributed to the difficulty in identifying the meniscal borders with manual segmentation. In the future, a computer program using artificial intelligence will be needed to identify the meniscal border accurately and facilitate calculation of the meniscal volume. Finally, the postoperative MRI examinations were performed only 3 months following the meniscal repair. This may underestimate the possible loss of reduction over time.

Nevertheless, this study is clinically relevant in that the volume change of meniscal extrusion at 90° knee flexion provides biomechanical confirmation that transtibial repairs can control the posteromedial translation of the meniscus and restore shock absorber function. It is also revealed that the root repair has limited ability to reduce meniscal extrusion, given the amount of extrusion seen in normal knees.

Conclusions

This study demonstrated that transtibial repair for MMPRT decreased the volume of meniscal extrusion 3 months following surgery. The volume reduction represented the increase in tibiofemoral contact volume, indicating that the repair holds the posterior anchor so as to recover the meniscal function of load transmission.

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Figure legends

Fig 1 Illustration of two suture methods

a Modified Mason-Allen technique with FasT- Fix (Smith & Nephew, Andover, MA, USA). The uncut FasT-Fix suture and the vertical suture using Ultrabrade (Smith & Nephew) were retrieved from the tibial tunnel at an anatomic attachment of the meniscal root. **b.** Two simple stitches technique using Knee scorpion (Arthrex, Naples, FL, USA). The first suture (no.2 Ultrabrade or UltraTape) is passed through the inner area of the root, and the second suture (UltraTape) is inserted into the outer area, more than 10 mm from the torn part. MFC, medial femoral condyle; MTP, medial tibial plateau; MM, medial meniscus; PCL, posterior cruciate ligament.

Fig 2 3D reconstructed images of MMPRT knee, visualized by SYNAPSE VINCENT® (Fuji Medical System, Tokyo, Japan)

a 3D model of meniscus, femur, and tibia at 10° knee flexion. **b** Measurement in the axial plane at 10°, including the meniscus within the articular joint (cyan area) and extrusion area (purple area). A reference line (red dotted line) was drawn intersecting the tibial intercondylar eminences. MMME (grey arrow) was the distance from the medial edge of the tibia (dashed grey line) to the meniscus (dotted grey line). MMPE (grey arrow) was the distance from the posterior edge of the tibia (dashed grey line) to the meniscus (dotted grey line). **c** The extrusion area (purple area) was defined as the region separated by a dashed line on the tibial edge. **d** 3D model of meniscus, femur, and tibia at 90°

knee flexion. **e** Measurement in the axial plane at 90°. MMME (grey arrow) and MMPE (perpendicular grey arrow). **f** The extrusion area (purple area) separated by a dashed line along the posteromedial corner of the tibia. The volume of intra-articular area (cyan area) was described as MMRV.

MMPRT, medial meniscus posterior root tear; MMME, medial meniscus medial extrusion; MMPE, medial meniscus posterior extrusion; MMRV, medial meniscus remaining volume

Fig 3 Postoperative change of 3D meniscal morphology in a 65-year-old male patient

a At 10°, the extruded meniscus (purple area) is located along the medial side. **b** At 90°, the meniscal root is detached from the posterior attachment. The meniscus translated to the posteromedial direction with MMPE and its thickness. **c** Postoperatively, the reduction of the purple area is partially observed at 10°. **d** At 90°, the posterior root is stabilised and the purple area is reduced, with an increase in the intra-articular cyan area.

MMPE, medial meniscus posterior extrusion

Compliance with ethical standards

Conflict of interest

The authors report no conflicts of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional review board and the 1964 Helsinki declaration and its later amendments.