Biomechanical Comparison of Inside-Out and All-Inside Meniscal Repair in Controlling the Peripheral Gap and Extrusion of the Lateral Meniscus With a Complete Radial Tear

A Cadaveric Study Using a Robotic Simulator

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Background: Although both the classical inside-out and all-inside techniques are performed for the repair of complete radial tears, which should be the standard technique is, to the authors' knowledge, controversial considering the clinical outcomes and biomechanical studies. There are no biomechanical studies of repairs of the lateral meniscus (LM) evaluating the peripheral side gap (peripheral gap) of the radial tear site and extrusion of the LM, which seems to be important in the treatment of radial tears.

Purpose: To compare the inside-out and all-inside meniscal repair techniques by evaluating the peripheral gap and extrusion of the LM with complete radial tear using a 6 degrees of freedom robotic system and fresh-frozen cadavers.

Study Design: Controlled laboratory study.

Methods: This study was performed using 6 fresh-frozen cadaveric knee specimens, a robotic testing system, and ultrasound evaluation. Ultrasound evaluations were performed to measure peripheral gaps and extrusions. The first ultrasound evaluation under 5 N·m of valgus load was performed on the knee at 30° and 90° of flexion. After a complete radial tear at the midsegment of the LM was created, a second ultrasound evaluation under valgus load was performed. Finally, all-inside and inside-out meniscal repairs done with 1 horizontal suture were performed on the same knee in a randomized order. Subsequently, the third and fourth ultrasound evaluations under valgus load were performed.

Results: The peripheral gap of the inside-out meniscal repair technique was significantly smaller than that of all-inside meniscal repairs at knee flexion angles of 30° and 90° (6.0 vs 11.5 mm and 5.6 vs 10.9 mm [both $P < .0167$], respectively). The extrusion of inside-out meniscal repair was significantly smaller than that of all-inside meniscal repair at a knee flexion angle of 90° (2.6 vs 3.2 mm; $P < .0083$).

Conclusion: The inside-out meniscal repair technique showed less peripheral gap and extrusion of the LM in a complete radial tear than the all-inside meniscal repair. Inside-out repair may be advantageous for radial tears over all-inside repair because only inside-out repair can tighten the peripheral side of the radial tear.

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Clinical Relevance: The LM with a complete radial tear should be repaired using the inside-out technique.

Keywords: all-inside; inside-out; knee; meniscal repair; meniscus; peripheral gap; ultrasound

The importance of the meniscus in the knee joint is well known.[13,17] Complete radial tears transect the circumferential collagen fibers responsible for load distribution and dispersion of hoop stresses.[10] It has been reported that radial tears are related to increased contact pressures and decreased contact areas at the surrounding articular surfaces.[3,18] Reportedly, meniscal injuries, including radial tears, lead to higher degrees of meniscal extrusion and the progression of osteoarthritis compared with other types of meniscal injuries.[2,14] In addition, the clinical success of meniscal repair for radial tears may still be limited.[16] Recently, a variety of radial tear repair techniques have emerged. While the inside-out technique remains the gold standard for meniscal repair, all-inside repairs are becoming increasingly popular. Modern all-inside repair devices deploy anchors outside the periphery of the meniscus or capsule in various configurations to simulate inside-out repair without the need for extra incisions and their resultant complications. Multiple reviews have been performed on the outcomes of all-inside repair compared with inside-out repair, with the vast majority of included all-inside studies using capsular-based devices.[12,24,25] A systematic review[19] on biomechanical studies of meniscal repairs reported that there are no apparent differences between inside-out and all-inside meniscal repairs.

However, most of the previous biomechanical studies dealing with meniscal repair were nonphysiological studies in which menisci were removed from cadavers or animal knees. They were then placed on a uniaxial material testing machine to measure the gap created at the injured site after cyclic loading and the failure mode was analyzed.[19] The menisci are loaded by a dynamic combination of compressive and shearing forces that underscore the necessity for primary stability. To test the efficacy of the suture construct, studies that mimic circumstances in which menisci are loaded with a femoral and tibial relationship that is a relatively physiological condition, not isolated from knee joints, are needed. Current all-inside devices used for repair of radial tears place the suture horizontally in a fashion similar to that of an inside-out repair but without fully encircling the tear at the peripheral side.[23] We believe that repairs of the lateral meniscus (LM) should close the peripheral side gap (peripheral gap) of the radial tear site. Theoretically, the peripheral gap leads to meniscal extrusion, which has gained attention because it is related to load distribution (Figure 1).[15,22]

Moreover, vascular supply of the peripheral side of the meniscus has been reported to be sufficient for healing.[1] Because of this inherent anatomic characteristic, there is an emphasis on encouraging peripheral meniscal healing. Currently, no study has investigated the peripheral gap of the radial tear site. Although the results of many nonphysiological biomechanical studies using menisci separated from the knee joint have shown that there is no difference between both techniques,[19] the peripheral gap and extrusion of the meniscus after meniscal repair in the relatively physiological knee joint specimen have not been sufficiently investigated.

This cadaveric study aimed to compare the effect of horizontal inside-out and all-inside meniscal repair by evaluating the peripheral gap and extrusion of the LM with complete radial tear using fresh-frozen cadavers, a robotic system, and ultrasound evaluation. We hypothesized that the inside-out meniscal repair technique would show less peripheral gap and extrusion of the LM in a complete radial tear than the all-inside meniscal repair.

METHODS

Specimen Preparation

The study protocol to obtain, use, and dispose of fresh-frozen human cadaveric knees was approved by the ethics committee of our institution (approval No. 1-2-68). Six fresh-frozen knee specimens (mean age at death, 82.0 years; range, 71-90 years) were obtained from a donation to the university anatomy program. Informed consent was obtained from the individuals before death. Physical

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Ethical approval for this study was obtained from Sapporo Medical University (No. 1-2-68).

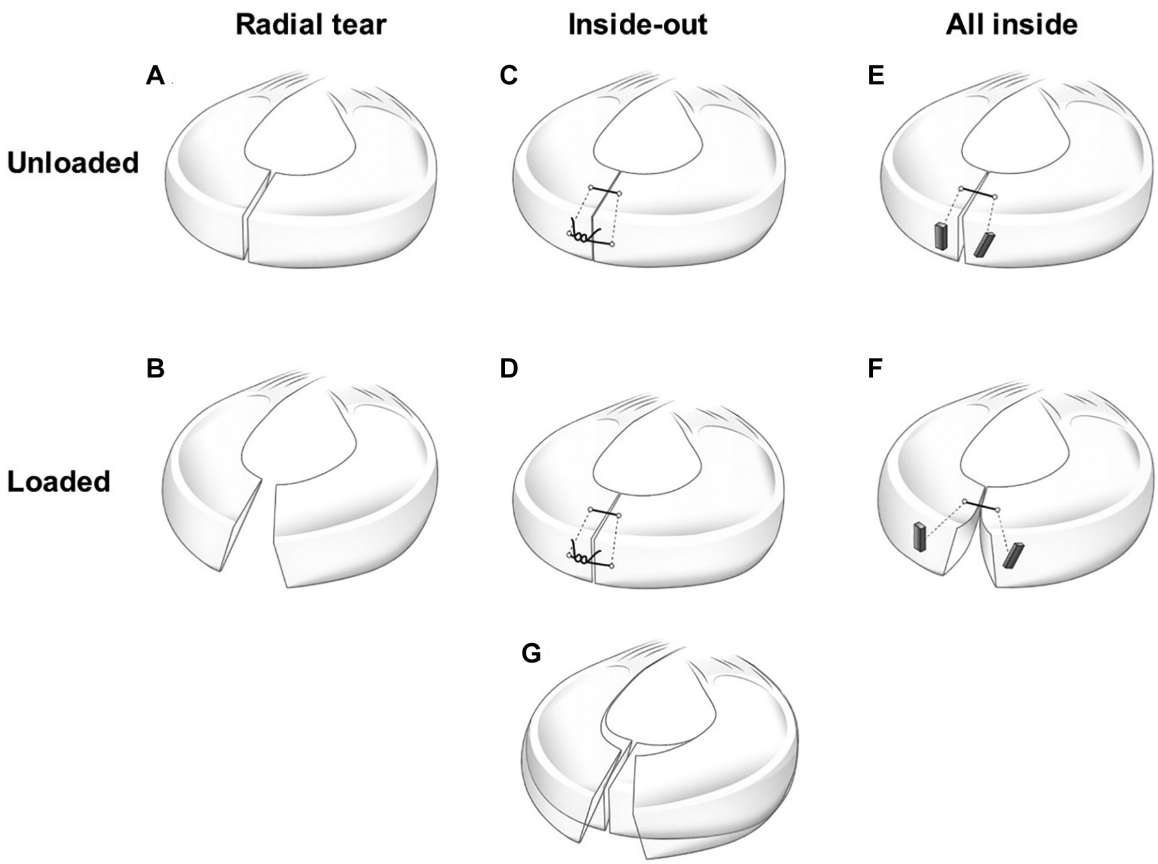

Figure 1. Theoretical schemas of each state of the lateral meniscus (LM). (A) Unloaded LM with complete radial tear. The radial tear site is closed from the central rim to the peripheral side. (B) Loaded LM with complete radial tear. The radial tear site is opened from the central rim to the peripheral rim. (C) Unloaded LM after inside-out repair. The radial tear site is closed from the central rim to the peripheral rim. (D) Loaded LM after inside-out repair. The radial tear site is almost closed from the central rim to the peripheral rim. (E) Unloaded LM after all-inside repair. The radial tear site is closed from the central rim to the peripheral rim. (F) Loaded LM after all-inside repair. Although the radial tear site is almost closed at the central rim, it is open at the peripheral rim. (G) Superimposition of Figure 1, A and B. The schema shows that the peripheral gap leads to meniscal extrusion.[1234]

examinations were performed before biomechanical testing to ascertain ligamentous stability and range of motion (ROM) from full extension to 130° of flexion. Specimens with ligamentous instability or loss of ROM were excluded (n = 2). The specimens were thawed at room temperature for at least 24 hours before testing. Each specimen was then kept wet to preserve tissue integrity during the test. The femur and tibia were cut at least 15 cm above and below the joint line, and the fibula was cut 5 cm below the proximal tibiofibular joint. The soft tissues, including all the muscles except the popliteus and the patella, were excised, whereas the ligaments, posterior capsule, and meniscus were left intact. Both ends of the tibia and femur were fixed using acrylic resin (Ostron II; GC) and poured into a cylindrical mold. The fibula was fixed in its original position using resin. The femoral and tibial cylinders were fixed with aluminum clamps and connected to the end effector of the robotic testing system[8] (FRS-2015; Technology Service) (Figure 2A).

Surgical Procedure

Both inside-out and all-inside meniscal repairs were performed on the same knee, and the testing order of the 2 meniscal repairs was randomized. Both repairs were performed in a horizontal and single-stitch fashion. The sutures were placed on the femoral side of the LM, 5 mm on either side of the tear and at the center between the central and peripheral rims (Figure 1). All-inside meniscal repairs were performed using an AIR meniscal repair system (Stryker), which deploys anchors to the periphery of the meniscus and capsule. Inside-out meniscal repair was performed using inside-out sutures with the Henning meniscal suture kit (Stryker). The inside-out repair suture was secured with 2 square knots and 5 throws on the capsular side of the meniscus. After the first meniscal repair and subsequent tests were completed, the first suture was removed and the second meniscal repair surgery was performed using the same route within the LM.

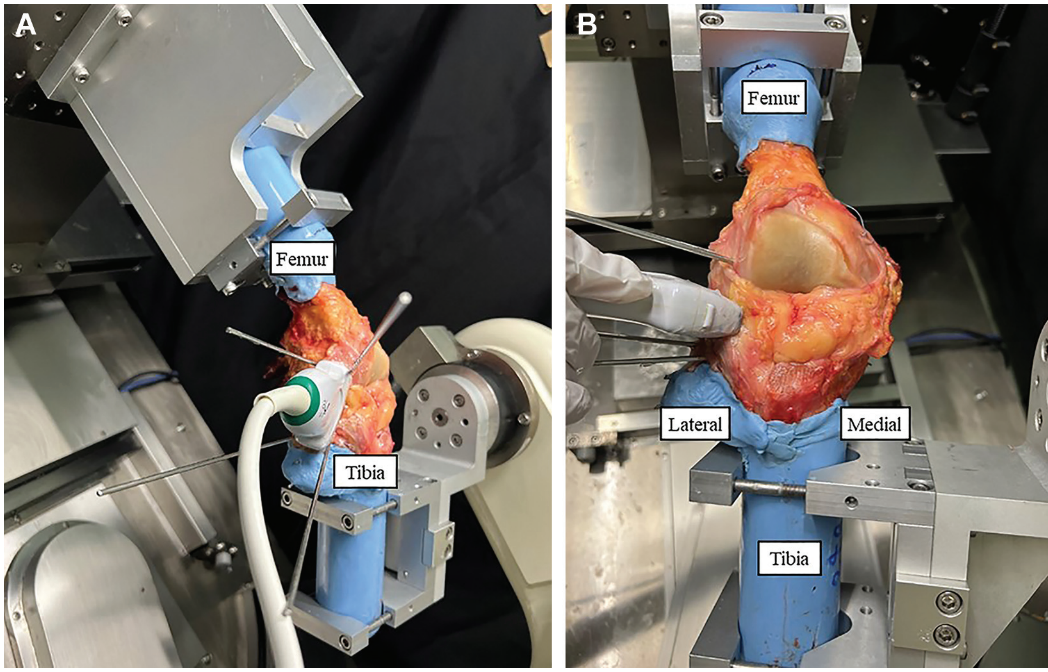

Figure 2. Robotic testing system and ultrasound evaluation for (A) peripheral gap and (B) extrusion on a right knee. The manipulator, which works with the universal force-torque sensor, is placed on the end effector. The tibia is fixed on the end effector, and the femur is fixed to the device using metal clamps. After the appropriate position of the probe was determined, the 4 pins were inserted around the probe to make the repeated examination more accurate.

Testing Apparatus

A robotic testing system with a custom-made manipulator with 6 degrees of freedom equipped with a universal force-torque sensor (DELTA IP65, SI-660-60; ATI Industrial Automation) was used (Figure 2A).[5] The robotic system can simulate physiological knee joint motion with respect to the joint coordinate system developed by Grood and Suntay in vitro.[7] This system, which guides the displacement and force or torque applied to knee joints, is controlled in real time by a LabView-based program (Version 1.0.0.0; National Instruments Corp) running on a Windows PC (Microsoft Corp).

Testing Protocol

First, the flexion-extension axis of the knee was defined as 0° of flexion when a 0.5-N·m extension moment was applied to the intact knee. Next, passive flexion-extension was performed from its hyperextended position, with an extension moment of 5 N·m and knee flexion of 120°. The passive flexion-extension was repeated 3 times as preconditioning, at a rate of 0.5 deg/s. To maintain tibiofemoral articular contact, 10 N of axial force was applied throughout the experiment. The first ultrasound evaluation under 5 N·m of valgus load was performed on the knee at 30° and 90° of knee flexion. After testing the intact knee, a complete radial tear at the midsegment of the LM was created using a No. 11 scalpel blade for arthroscopy. Then, a second ultrasound evaluation under valgus load was performed. Finally, all-inside and inside-out meniscal repairs were performed on the same knee in a randomized order. Third and fourth ultrasound evaluations were performed after each repair, respectively.

Before each test of each knee status, preconditioning, 5 N·m of valgus load, and 250 N of axial load at 30° and 90° of flexion were applied to the knee 3 times to minimize the effects of creep.

Ultrasound Evaluation of the Peripheral Gap and Extrusion of the LM

A 10-2 MHz linear transducer (Aixplorer version 12 and SL10-2; Supersonic Imagine) was used to evaluate the LM. One orthopaedic surgeon (K.S.) performed the ultrasound examination, and another (K.T.) performed the measurements of the peripheral gap and extrusion using the provided ultrasound software with an accuracy of 0.1 mm. Both surgeons have 7 years of ultrasound experience. The examinations were repeated 3 times at each knee status, and the median values were adopted.

First, extrusion was measured similarly to that of a previous study.[21] Ultrasound examinations were performed using long-axis scans 10 mm anterior to the lateral collateral ligament (Figure 2A). Extrusion was defined as the distance between the outermost border of the LM and the line connecting the lateral borders of the joint surfaces of the femur and tibia (Figure 3A). After the appropriate position of the probe was determined, the 4 pins were inserted

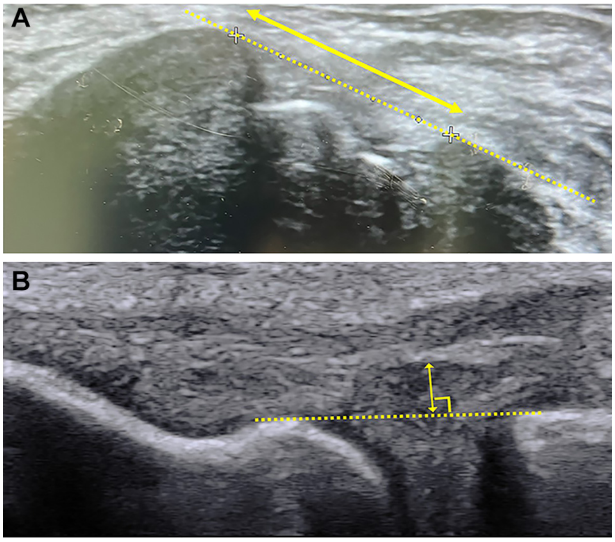

Figure 3. (A) Short-axis ultrasound image of the lateral meniscus (LM) at the center level. A line (dotted line) tangential to both portions of the LM anterior and posterior horns to the complete radial tear was drawn. The peripheral gap (double-headed arrow) is defined as the distance between the 2 tangent points. (B) Long-axis ultrasound image of the LM 10 mm anterior to the lateral collateral ligament. Extrusion (double-headed arrow) is defined as the distance between the outermost border of the LM and the line (dotted line) connecting the lateral borders of the joint surfaces of the femur and tibia.

around the probe to make the repeated examination more accurate.

Then, for peripheral gap measurement, ultrasound examinations were performed using short-axis scans at the center level of the LM (Figure 2B). A line tangent to both portions of the LM anterior and posterior to the complete radial tear was drawn. The peripheral gap was defined as the distance between the 2 tangent points (Figure 3B). This peripheral gap measurement by ultrasound evaluation by several examiners was confirmed to coincide with the evaluation using a digital caliper by direct visualization after joint capsule removal in the pilot studies (Figure 4). The intraclass correlation coefficient between the ultrasound and direct measurements was 0.88.

Statistical Analysis

The peripheral gap and extrusion under valgus load for the intact knee state, complete radial tear state, all-inside repair state, and inside-out repair state were analyzed using a 2-factor repeated-measures analysis of variance with post hoc pairwise comparison using Bonferroni correction to compare the state of the knee and the knee flexion angle. All analyses were performed using the Statistical Package for Social Sciences Version 28.0 (IBM Corp). Statistical significance was set at a P value $<.05$. A post hoc power analysis was performed to determine the power of the study. Based on the means and standard deviations of the peripheral gap and extrusion, the power of this study was 0.881 to 1.000.

The intraclass correlation coefficients of intra- and interobserver reliability between the ultrasound measurements were 0.97 to 1.00. First, the ultrasound examination was performed by K.S. and the measurements were performed by K.T. Then, the ultrasound examination was performed by K.T. and the measurements were performed by K.S.

RESULTS

The results for the peripheral gap are shown in Figure 5A, indicating that the peripheral gap of inside-out meniscal repair was significantly smaller than that of all-inside meniscal repair at knee flexion angles of 30° and 90° (both $P < .0167$).

The results of extrusion are shown in Figure 5B. The results showed that the extrusion of inside-out meniscal repair was significantly smaller than that of all-inside meniscal repair at a knee flexion angle of 90° ($P < .0083$).

DISCUSSION

This cadaveric study compared inside-out and all-inside meniscal repairs by evaluating the peripheral gap and extrusion of the LM with a complete radial tear. The results showed that the peripheral gap and extrusion of inside-out meniscal repair were significantly smaller than those of all-inside meniscal repair.

Although a systematic review of the biomechanical studies[19] was inconclusive regarding the superiority of inside-out or all-inside repair, the results of the present study concluded that inside-out repair was superior. We speculate this difference is because of the testing condition. Most of the previous biomechanical studies were performed with menisci isolated from the knee joint, which is a nonphysiological condition. On the contrary, the present biomechanical study was performed on the meniscus after meniscal repair in the relatively physiological knee joint condition. In addition, the evaluation methods, peripheral gap and extrusion, seem to be more related to the healing process of the radial tear site or clinical outcomes. These are the strengths of this study.

Meniscal extrusion, which is theoretically related to the peripheral gap of a radial tear (Figure 1), has been reported to be important because it is a crucial predictor of knee cartilage loss[22] and joint space narrowing.[15] The extrusion and the peripheral gap are important because the success of meniscal healing largely depends on the primary fixation strength and the resistance capacity against gap formation during repetitive loading. Considering the smaller extrusion and peripheral gap in the inside-out repair group, inside-out meniscal repair should be more adequate for a complete radial tear of the LM than all-inside meniscal repair.

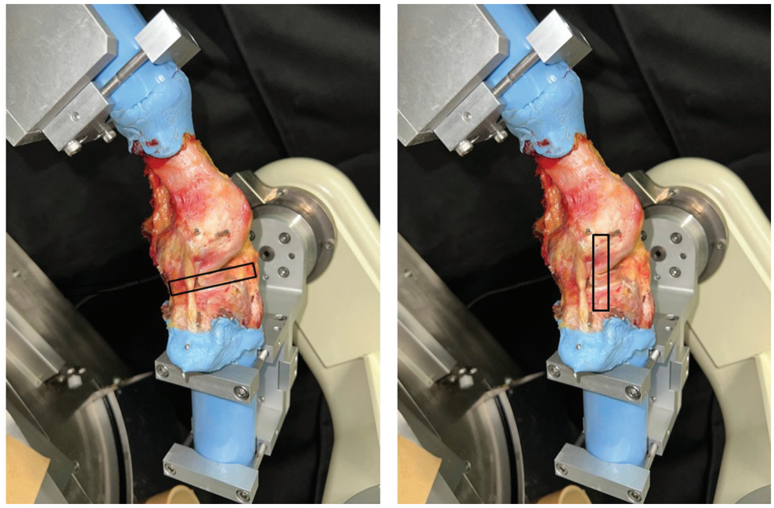

Figure 4. Direct visualization of the peripheral gap of the complete radial tear site of the lateral meniscus after joint capsule removal in a pilot study. The peripheral gap measurement using ultrasound evaluation by several examiners was confirmed to coincide with the evaluation performed using a digital caliper by direct visualization.

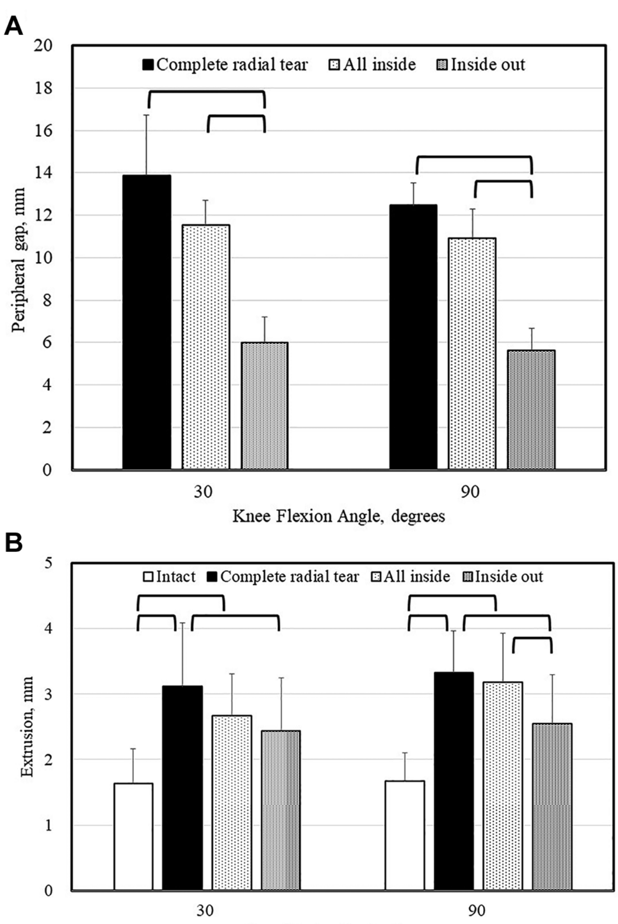

Figure 5. Results of (A) peripheral gap and (B) extrusion of the lateral meniscus (LM) at each knee flexion angle tested in each knee state under 5 N·m of valgus load. Rectangles indicate a significant different.

In general, whether inside-out or all-inside meniscal repair should be the gold-standard technique remains controversial.[12] The all-inside technique has merits, such as a short operation time and low risk of neurovascular injury.[11] Despite these benefits, other randomized controlled trials[9] have suggested that arthroscopic meniscal repair with the inside-out technique is superior to other techniques. A systematic review[19] of biomechanical studies of meniscal repairs reported that there are no apparent differences between all-inside and inside-out meniscal repairs with regard to load to failure, stiffness, or displacement. However, considering the results of the present study, which investigated the movement and stability of the repaired meniscus in the knee joint, we believe that inside-out meniscal repair is superior to all-inside meniscal repair for complete radial tears.

Figure 6 shows an arthroscopic view of the LM with a complete radial tear and all-inside repair during the pilot study.

Although the meniscus appears to be reduced after all-inside repair, the results of the present study showed that the peripheral gap of the LM after all-inside repair was large. This discrepancy between the arthroscopic view (similar to that shown in Figure 6) and the results of the present study can be explained in 2 ways. First, the repaired meniscus is arthroscopically observed with compartment traction. Surgeons cannot observe the meniscus with compressive loading of the compartment and meniscus, although the meniscus is loaded postoperatively during rehabilitation and daily activities. Therefore, meniscal repair should be performed considering loading conditions. A more important point with respect to repairing a complete radial tear is that surgeons must make the decision considering not only the reduction and resistance capacity against gap formation of the central side of the radial tear site of the meniscus, which is observed during

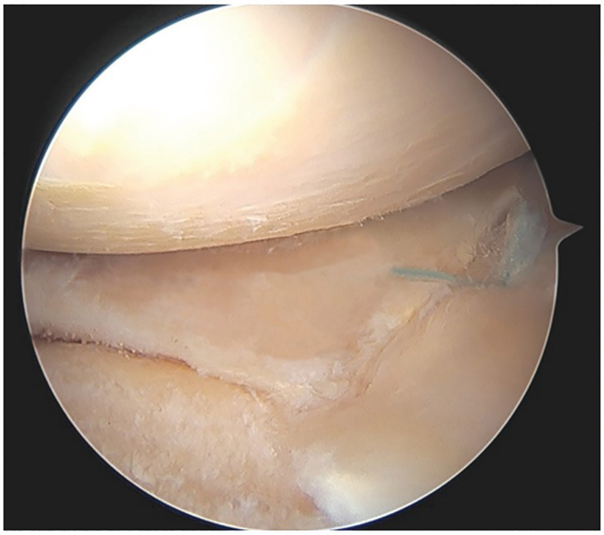

Figure 6. Arthroscopic view of the lateral meniscus with a complete radial tear and all-inside repair during the pilot study. The meniscus appears to be reduced after all-inside repair in the arthroscopic view.

arthroscopy, but also those of the peripheral side (Figure 1). From this perspective, all-inside meniscal repair does not control the peripheral side of the complete radial tear. Therefore, the peripheral gap of the meniscus with all-inside repair in the present study was not different from that of the radially torn meniscus without treatment. Conversely, inside-out repair can tighten both the central and peripheral sides of the radial tear site of the meniscus (Figure 1). Therefore, the peripheral gap of the meniscus with inside-out repair was considerably smaller than that of others.

The peripheral gap was >5 mm, even in the inside-out repair group, leading to 2 insights. First, although both repairs were performed in the usual, simple horizontal and single-stitch fashion in the present study, meniscal repairs for complete radial tears should be performed with more than a single suture to acquire more stability for the peripheral gap. Second, if the repaired meniscus is loaded immediately after surgery, the repaired radial tear site may open. Therefore, it may be appropriate to limit postoperative weightbearing until the radial tear site has healed to some extent.

The failure rates of meniscal repair of the previous reports range from 19% to 30%.[4,6,8,12,20,26] We speculate that the main reason for the high failure rates may be due to a lack of appropriate decision-making for each type of meniscal tear. A meta-analysis investigating 864 meniscal repair cases[24] reported that there was no difference in the rate of the revision surgery 5 years after meniscal repair regarding the site or type of meniscal injury. With respect to surgical technique, the rate of revision surgery for inside-out meniscal repair resulted in a lower failure rate (5.6%) compared with all-inside meniscal repair (22.3%), although this finding is controversial when are other studies are taken into consideration. One of the possible reasons for this difference is a technical error, including device migration after all-inside meniscal repair.[25] However, we believe that this factor alone cannot explain the large difference in the revision surgery rate after all-inside meniscal repair. The present study only investigated the peripheral gap for complete radial tears and elucidated the superiority of inside-out repair compared with all-inside repair. However, we postulate that there may be some unnoticed concepts for other types of meniscal injury. We believe that recognizing and investigating these unknown concepts can be key to improving the clinical outcomes of meniscal repair surgery.

Limitations

This study has several limitations. First, only gap formation on the peripheral side of the radial tear site of the meniscus was evaluated. Gap formation on the central side was not evaluated. This is because gap formation on the central side was extremely difficult to evaluate by direct visualization or ultrasound imaging with compressive loading to the lateral compartment and the LM under 5 N·m of knee valgus loading. Second, although there are a variety of radial tear repair techniques, only the inside-out and all-inside repair techniques in a horizontal and single-stitch fashion were performed in the present study to minimize biases such as order bias. Third, although no degeneration or damage of the meniscus or cartilage was macroscopically found throughout the experiments, the experiments were performed using specimens from older donors with low-quality bone and degenerative tendons, which could have caused potential biases. Fourth, since the study results were obtained through cadaveric tests, muscle forces and the contribution of soft tissues—such as the capsule and extensor mechanism—which had been excised during specimen preparation, were disregarded.

CONCLUSION

The inside-out meniscal repair showed better performance in controlling the peripheral gap and extrusion of the LM with a complete radial tear than the all-inside meniscal repair.

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