

Quantitative Evaluation of Dynamic Lateral Meniscal Extrusion After Radial Tear Repair

Philipp W. Winkler,^{*†} MD, Guido Wierer,^{‡§} MD, Robert Csapo,^{*‡} PhD, Assoc Prof, Caroline Hepperger,^{*‡}, Bernhard Heinzle,^{||} MD, Andreas B. Imhoff,[†] MD, Prof, Christian Hoser,^{*‡} MD, Priv-Doz, and Christian Fink,^{*‡¶} MD, Prof

Investigation performed at Sports and Joint Surgery, Gelenkpunkt, Innsbruck, Austria

Background: Radial tears of the lateral meniscus frequently accompany acute anterior cruciate ligament (ACL) injuries and lead to increased joint stress and pathological meniscal extrusion (ME). The dynamic behavior of the lateral meniscus after radial tear repair with respect to ME has not been described.

Purpose: To quantitatively assess dynamic lateral ME after all-inside radial tear repair.

Study Design: Case series; Level of evidence, 4.

Methods: Patients who underwent ACL reconstruction and all-inside radial tear repair of the lateral meniscus and had no history of contralateral knee injuries were included. Magnetic resonance imaging scans were acquired in loaded (50% of body weight) and unloaded conditions of both the injured and noninjured knees. A custom-made pneumatically driven knee brace was used for standardized knee positioning in 10° of flexion and with axial load application. Quantitative measures included the absolute lateral ME, meniscal body extrusion ratio, and Δ extrusion. Preoperative and postoperative unloaded extrusion data were compared by paired *t* tests. For postoperative data, the concomitant influence of the factors “leg” and “condition” were assessed through factorial analyses of variance.

Results: A total of 10 patients with a mean follow-up of 47.9 months were enrolled. The intraclass correlation coefficient (ICC) confirmed good interrater reliability (ICC, 0.898) and excellent intrarater reliability (ICC, 0.976). In the unloaded injured leg, all-inside repair reduced ME from 3.15 ± 1.07 mm to 2.13 ± 0.61 mm (−32.4%; *P* = .033). Overall, load application led to a significant increase in ME (+0.34 mm [+21.8%]; *P* = .029). Significantly greater ME was observed in the injured knee (+1.10 mm [+93.2%]; *P* = .001) than in the noninjured knee. The condition × leg interaction was not significant (*P* = .795), suggesting that the compression-associated increase in ME did not differ significantly between the injured and noninjured knees.

Conclusion: Lateral ME depends on the knee status and loading condition. All-inside repair of radial meniscal tears led to a reduction of extrusion with no alteration in dynamic lateral ME. Meniscus-preserving therapy is recommended in the case of a radial lateral meniscal tear to preserve its dynamic behavior.

Keywords: dynamic meniscal extrusion; lateral meniscus; magnetic resonance imaging; radial tear; meniscal suture repair; stress MRI

The menisci play an important role in knee joint biomechanics. Because of their composition, morphology, and structural configuration, they are indispensable for proper knee functioning. In addition to decreasing tibiofemoral contact pressure and increasing contact area and congruency, they substantially contribute to load transmission, shock absorption, stability, nutrition, lubrication, and proprioception of the knee.^{19,35,38} The incidence of meniscal tears associated with anterior cruciate ligament (ACL) lesions is as high as 79%, with the lateral meniscus being more frequently affected than the medial meniscus in acute circumstances.^{17,22,31} Radial meniscal tears represent

approximately 15% of meniscal injuries and mainly affect the lateral meniscus.^{24,37} For the combination of radial tears of the lateral meniscus and ACL lesions, an incidence of 5.4% has been reported.¹⁷

Under load-bearing conditions, axial force acting on the knee causes a radially oriented force vector because of the wedge-shaped appearance of the meniscus. The resulting force leads to radial displacement of the menisci, which is also known as meniscal extrusion (ME). Circumferentially oriented collagen fibers of the menisci prevent pathological extrusion by generating hoop stress.^{19,38} These circumferential fibers run from the anterior to posterior root and are disrupted in the case of a radial tear, which leads to substantial impairment of meniscus function.^{28,38} Injuries and degeneration of the meniscal substance and meniscus root tears are associated with significantly increased ME.^{14,30,33}

The Orthopaedic Journal of Sports Medicine, 8(4), 2325967120914568
DOI: 10.1177/2325967120914568
© The Author(s) 2020

This open-access article is published and distributed under the Creative Commons Attribution - NonCommercial - No Derivatives License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits the noncommercial use, distribution, and reproduction of the article in any medium, provided the original author and source are credited. You may not alter, transform, or build upon this article without the permission of the Author(s). For article reuse guidelines, please visit SAGE's website at <http://www.sagepub.com/journals-permissions>.

The degree of radial displacement depends on the severity and type of the meniscal lesion.²⁸ A radial meniscal tear results in ME, which leads to a significantly decreased contact area and increased contact pressure.⁴¹ These biomechanical findings can be compared with the effect of partial or total meniscectomy.²⁰ Therefore, pathological ME is sometimes termed “functional meniscectomy.” The increased tibiofemoral contact pressure accelerates cartilage degeneration, resulting in a progressive development of knee joint osteoarthritis.^{5,29,49}

Currently, no consensus exists regarding the optimal treatment of radial meniscal tears. Partial meniscectomy has become the most frequently performed orthopaedic surgery in the United States.²¹ Hence, numerous studies have shown accelerated degenerative cartilage loss with the subsequent development of knee osteoarthritis,^{3,34,43,46} particularly after lateral meniscectomy.²⁷ Comparative studies have suggested that meniscal repair techniques may yield superior clinical and radiological outcomes, especially at long-term follow-up.^{34,49} For this reason, interest in meniscus-preserving treatment methods has increased in recent years. Because the biomechanical understanding of radial meniscal lesions is constantly improving, extensive research has focused on treatment options for this special tear pattern.^{1,12,13,23,39,45,47,51}

The purpose of the present study was to quantitatively analyze dynamic lateral ME in patients undergoing ACL reconstruction and radial tear repair of the lateral meniscus. For this study, magnetic resonance imaging (MRI) was used in combination with a pneumatic knee brace to simulate normal weightbearing. In all patients, both knees were examined for a comparison of the injured knee with the noninjured contralateral knee. It was hypothesized that lateral ME would decrease after all-inside radial tear repair but still remain significantly higher in the injured knee than in the contralateral noninjured knee. Additionally, it was hypothesized that lateral ME would increase bilaterally after axial load application and that the dynamic behavior would not differ between the injured and noninjured knees after radial tear repair.

METHODS

Patients who underwent ACL reconstruction and all-inside radial tear repair of the lateral meniscus were reviewed for eligibility. Selected patients had to visit the outpatient

clinic once for a detailed follow-up examination. The follow-up included obtaining patient history, recording patient-reported outcomes (PROs), conducting a clinical examination, and acquiring MRI scans. All examinations were performed on both knees. MRI scans were acquired with and without axial load application. Preoperative assessments were carried out retrospectively and included a standard clinical examination based on the International Knee Documentation Committee (IKDC) form, PRO measures, and MRI without axial knee loading.

Ethical permission was granted by the ethical review committee of the Medical University of Innsbruck in February 2018. Verbal and written consent for participation were obtained from all patients after providing detailed information about this project.

Patient Selection and Surgical Technique

The database of our specialized orthopaedic surgery clinic was screened for patients treated for a traumatic ACL injury in combination with a radial tear of the posterior horn of the lateral meniscus between 2010 and 2017 using a 1-stage procedure. To be included in the study, patients had to meet the criteria for inclusion summarized in Table 1. For primary ACL reconstruction, quadriceps, hamstring, or patellar tendon autografts were used. Radial meniscal tear repair was performed by the all-inside suture technique using ULTRA FAST-FIX (Smith & Nephew). Depending on the tear size, 1 to 3 sutures were placed to secure meniscal damage. Only partial and complete tears resulting in arthroscopically confirmed instability of the lateral meniscus were repaired.

Patient-Reported Outcomes

Patients were instructed to complete a questionnaire that was used to collect demographic data and included PRO measures and a visual analog scale (VAS) for pain. The PRO measures included the Lysholm score, Tegner activity level (TAL), subjective IKDC form, and Knee injury and Osteoarthritis Outcome Score (KOOS). The TAL, Lysholm, and VAS for pain scores were collected preoperatively, 6 and 12 months postoperatively, and at the final follow-up. The KOOS and subjective IKDC scores were only acquired at the final follow-up.

*Address correspondence to Christian Fink, MD, Prof, Sports and Joint Surgery, Gelenkpunkt, Olympiastraße 39, 6020 Innsbruck, Austria (email: c.fink@gelenkpunkt.com).

*Sports and Joint Surgery, Gelenkpunkt, Innsbruck, Austria.

†Department of Orthopaedic Sports Medicine, Klinikum Rechts der Isar, Technical University of Munich, Munich, Germany.

‡Research Unit for Orthopaedic Sports Medicine and Injury Prevention, Institute of Sports Medicine, Alpine Medicine and Health Tourism, University for Health Sciences, Medical Informatics and Technology, Hall in Tirol, Austria.

§Department of Orthopaedics and Traumatology, Paracelsus Medical University, Salzburg, Austria.

||Department of Radiology, MRT-CT Diagnostics, Wörgl, Austria.

Final revision submitted December 9, 2019; accepted December 23, 2019.

One or more of the authors has declared the following potential conflict of interest or source of funding: A.B.I. has received consulting fees from ArthroSurface and Medi Bayreuth and royalties from Arthrex. C.F. has received consulting fees from Medacta and royalties from Karl Storz and Medacta. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval of this study was obtained from the Ethikkommission der Medizinischen Universität Innsbruck (No. 1251/2017).

TABLE 1
Inclusion and Exclusion Criteria^a

Inclusion Criteria	Exclusion Criteria
Minimum age at index surgery: 18 y	Horizontal, longitudinal, or complex meniscal tear
Maximum age at index surgery: 40 y	Partial meniscectomy
Primary ACL injury	Meniscus root tear
Radial tear of the posterior horn of the lateral meniscus	Radial tear limited to avascular zone 3 according to Arnoczky and Warren ⁴
ACL reconstruction	Ipsilateral ACL or lateral meniscal reinjury
All-inside suture repair	Contralateral ACL, complex knee, or lateral meniscal injury
Minimum follow-up: 12 mo	

^aACL, anterior cruciate ligament.

Clinical Examination

The clinical examination of the knee was based on the objective IKDC form. To avoid unnecessary radiation exposure with full-leg radiographs, the mechanical axis of the lower limb was assessed clinically. To quantify lower limb alignment, the caliper and goniometer methods described by Navali et al⁴⁰ and Hinman et al²⁵ were used. To evaluate the meniscal status, several tests including palpation of the joint line, the McMurray test, and the Thessaly test⁷ were performed.

Magnetic Resonance Imaging

MRI scans of both knees were acquired using a MAGNETOM Skyra 3.0-T MRI scanner (Siemens Healthineers). The MRI protocol included the following sequences: coronal, sagittal, and axial fat-suppressed proton density-weighted turbo spin echo for both conditions. The following parameters were used for imaging acquisition: coronal (repetition time/echo time [TR/TE] = 4330/30 ms; field of view [FOV] = 130 × 130 mm; slice thickness = 2 mm), sagittal (TR/TE = 2610/30 ms; FOV = 130 × 130 mm; slice thickness = 2 mm), and axial (TR/TE = 1950/29 ms; FOV = 150 × 150 mm; slice thickness = 2 mm). An MRI-compatible custom-made pneumatic knee brace (Ergospect) was used for standardized patient positioning and axial load application (Figure 1). Neutral rotation of the lower leg and 10° of knee flexion in a supine position were standard for imaging acquisition. The MRI examination started with the healthy knee, followed by the operated knee. First, scans were acquired in the unloaded condition. By using a pneumatic system within the knee brace, an axial force was then applied to induce stress equivalent to that caused by 50% of the patient's body weight acting on the knee joint in an upright stance. After imaging acquisition, the pneumatic knee brace was placed on the contralateral knee to repeat the process.

Preoperative scans were only available in the unloaded condition. Therefore, the preoperative data were compared

with the corresponding postoperative values of the operated unloaded knee.

Imaging Analyses

All MRI scans were analyzed by 2 experienced orthopaedic surgeons (P.W.W., G.W.) in collaboration with a musculoskeletal radiologist (B.H.). The 2 observers were blinded to the imaging acquisition conditions and assessed all MRI scans twice with 2 weeks between each assessment. For imaging evaluations and measurements, the free medical image viewer Horos version 3.3.5 (<https://horosproject.org>) was used.

Using the coronal slice in which the femoral attachment of the popliteal tendon was best visible, lateral ME was measured as the horizontal distance between the most external margin of the tibial plateau articular cartilage and the peripheral border of the lateral meniscus (Figure 2).^{11,42} The subchondral tibial plateau width (TW) was measured in the same layer and defined as the subchondral distance between the medial and lateral cartilage-bone transition. Using these values, the meniscus body extrusion ratio (MBER), which relates ME to the knee size,⁵² was calculated as ME/TW and expressed as a percentage. The difference in ME between the loaded and unloaded conditions (Δ extrusion)³⁰ was calculated for further analysis. Additionally, the MRI scans were reviewed for the presence of meniscofemoral ligaments (MFLs).

Statistical Analyses

Data analysis was performed by using SPSS Statistics software (Version 25.0, IBM). The level of significance for all statistical tests was set to .05.

To assess interrater reliability, all measurements of ME obtained before and after surgery, as well as in the unloaded and loaded conditions, were pooled (total n = 92) and compared between the 2 raters by means of a paired-samples *t* test. In addition, the intraclass correlation coefficient (ICC) was calculated using a 2-way random-effects model to quantify absolute agreement in the measurements.³² The typical error of measurement was calculated by dividing the standard deviation of the differences in scores by the square root of 2.²⁶ Correlation and Bland-Altman plots were created for visual inspection of agreement in the ratings. For test-retest (intrarater) reliability of data analysis, all MRI scans were reanalyzed by the main examiner (P.W.W.), and the ICC was calculated using a 2-way mixed-effects model.³² Further reliability statistics were calculated as for the interrater reliability analyses.

The efficacy of the treatment was evaluated through the statistical comparison of preoperative and postoperative data of ME and the respective MBER by means of paired-samples *t* tests. In addition, 2 × 2 factorial analysis of variance was used to analyze the effects of the factors "condition" (unloaded vs loaded) and "leg" (injured vs non-injured), as well as possible condition × leg interactions in the postoperative results. To analyze dynamic lateral ME, Δ extrusion was calculated for the healthy and injured knees and compared using a paired *t* test. For all significant

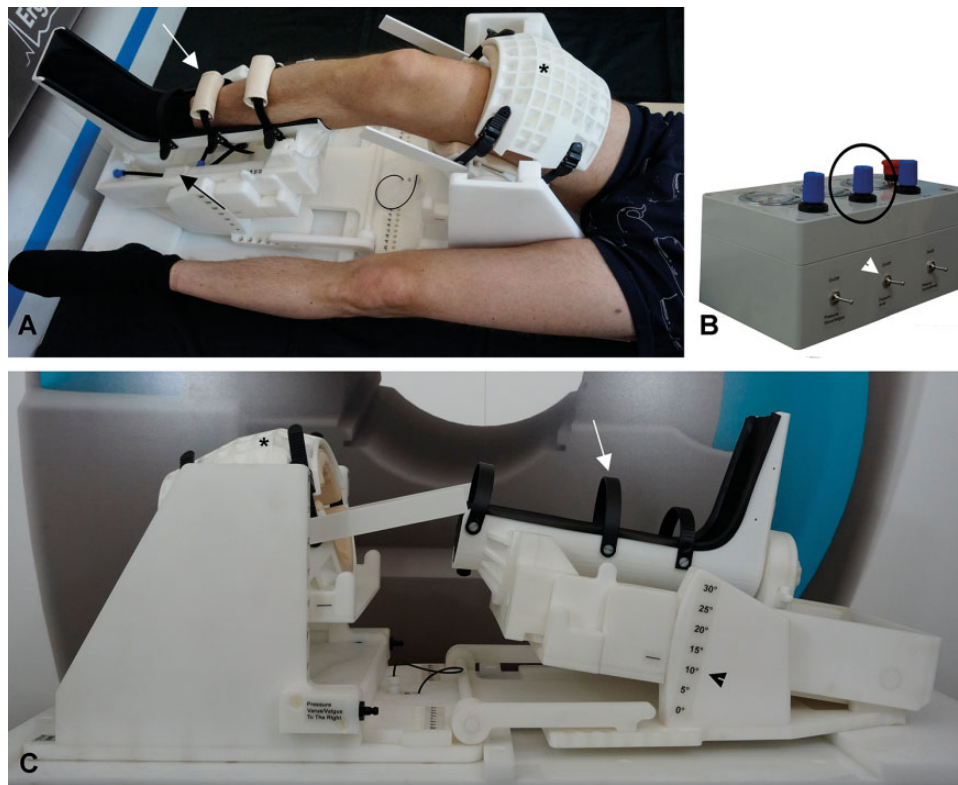


Figure 1. Magnetic resonance imaging-compatible pneumatic knee brace. (A) Knee fixed in the pneumatic brace. (B) Control panel. (C) Pneumatic knee brace from a lateral view. Asterisk = femoral fixation; white arrow = tibial fixation; black arrow = axial pneumatic cylinder; black arrowhead = flexion scale (10° in this case); white arrowhead = on/off switch of the pneumatic system; black circle = pneumatic pressure regulator.

effects, the Cohen d was calculated through t conversion,¹⁶ converted to Pearson r , and reported as measurements of effect sizes.

RESULTS

A total of 10 patients (9 male, 1 female) with a mean age of 25.30 ± 5.85 years at the time of surgery were included in this study. The mean body mass index was $22.98 \pm 1.94 \text{ kg/m}^2$. The mean time from injury to surgery was 6.9 days (range, 0-32 days), and the mean time from surgery to the final follow-up was 47.9 months (range, 12-87 months). For ACL reconstruction, the hamstring, quadriceps, and patellar tendon were used in 7 patients, 2 patients, and 1 patient, respectively. None of the meniscal tears affected the posterior root of the lateral meniscus. Moreover, 60% of the patients had a partial radial tear (>50% of the meniscal substance involved), whereas 40% had complete radial disruption of the posterior horn of the lateral meniscus. Also, 1 suture was applied in 6 patients, 2 sutures were applied in 3 patients, and 3 sutures were applied in 1 patient for radial tear repair. Radiological signs of radial tears could be found in 3 patients on postoperative MRI, although there was no confirmation of persistent lateral meniscal radial tears based on second-look arthroscopic surgery,

as there were no clinical signs or symptoms. Additional lesions of the medial meniscus and medial collateral ligament were each observed in 2 patients. During arthroscopic surgery, a grade 2 chondral lesion, according to the International Cartilage Repair Society classification system,¹⁰ was observed in the patellofemoral joint in 2 patients and in the medial compartment in 1 patient. In another patient, a grade 3 chondral lesion was detected in the medial compartment. The follow-up showed increasing tibiofemoral cartilage damage in 1 patient, whereas the others demonstrated consistent cartilage conditions. MRI scans revealed at least 1 MFL in 19 of 20 (95%) knees. The posterior MFL was present in 16 (80%) of the scanned knees, and the anterior MFL was present in 10 (50%). Both MFLs could be detected in 7 (35%) of the examined joints.

Measurement Reliability

On average, the measurements of ME obtained by the 2 raters agreed closely ($1.9 \pm 1.1 \text{ mm}$ [rater 1, P.W.W.] vs $2.0 \pm 1.1 \text{ mm}$ [rater 2, G.W.]) and were not statistically significantly different ($t[91] = -1.183$; $P = .240$). The ICC suggested good absolute agreement of the ratings (ICC, 0.898 [95% CI, 0.846-0.933]). The typical error of measurement was 0.5 mm (Figure 3).

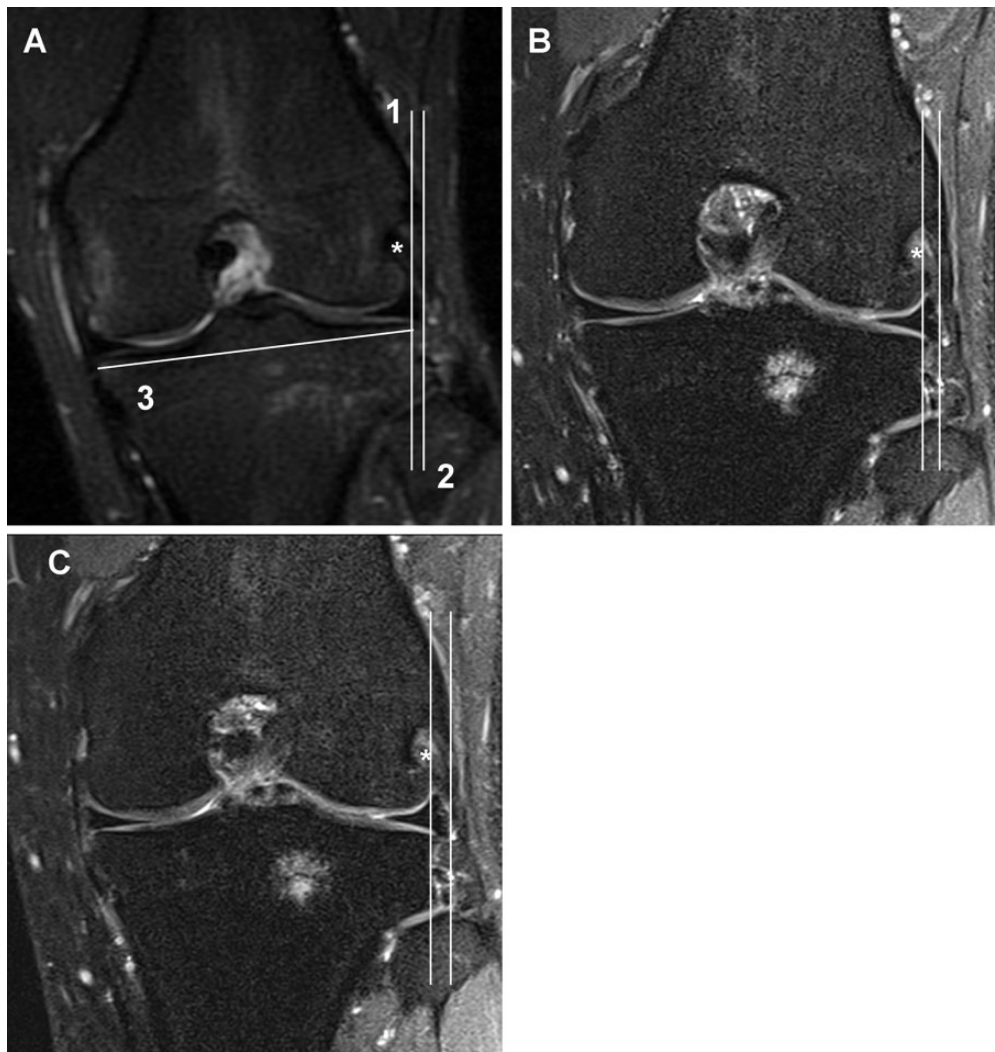


Figure 2. Lateral meniscal extrusion measurement. (A) Preoperative unloaded condition. (B) Postoperative unloaded condition. (C) Postoperative loaded condition. Asterisk = femoral attachment of the popliteal tendon; line 1 = vertical line running through the lateral tibial cartilage margin; line 2 = vertical line running through the most peripheral aspect of the lateral meniscus; line 3 = subchondral tibial plateau width; horizontal distance between lines 1 and 2 = absolute lateral meniscal extrusion.

The results obtained by rater 1 (P.W.W.) through repeated analyses of MRI scans differed by <0.1 mm on average (1.9 ± 1.1 mm vs 1.9 ± 1.0 mm, respectively; $t[45] = 0.986$, $P = .329$), and the difference was nonsignificant. Excellent reproducibility of imaging analysis was also confirmed by an ICC of 0.976 (95% CI, 0.957-0.987) and a typical error of measurement of 0.2 mm (Figure 4).

Lateral ME

In the unloaded injured leg, meniscal suture repair reduced ME from 3.2 ± 1.1 mm preoperatively to 2.1 ± 0.6 mm (-32.4%) at the final follow-up and the MBER from 4.17 ± 1.31 to 2.62 ± 0.64 (-37.2%), respectively. These changes were statistically significant and of moderate dimension (ME: $t[5] = 2.916$; $P = .033$; $r = 0.21$) (MBER: $t[5] = 3.335$; $P = .021$; $r = 0.57$). Analyses of postoperative ME

showed a significant effect of condition, ($F[1,9] = 6.731$; $P = .029$; $r = 0.21$), with extrusion being greater by 0.3 mm ($+21.8\%$) under compression (unloaded, 1.6 ± 0.9 mm; loaded, 1.9 ± 1.1 mm). Large differences were observed between legs: in the injured knee, ME was greater by 1.1 mm ($+93.2\%$), reflecting a significant effect of the factor leg, ($F[1,9] = 24.03$; $P = .001$; $r = 0.68$). The condition \times leg interaction was nonsignificant ($F[1,9] = 0.072$; $P = .795$), suggesting that the compression-associated increase in ME did not differ significantly between the injured and healthy knees. Analysis of the postoperative MBER showed similar results, with a significant effect of condition, ($F[1,9] = 6.841$; $P = .028$; $r = 0.15$), and leg ($F[1,9] = 25.888$; $P = .001$; $r = 0.54$) but no statistically significant condition \times leg interaction effect ($F[1,9] = 0.077$; $P = .787$). The mean values of ME and MBER depending on factors condition and leg are shown in Figure 5. Concerning dynamic behavior, mean Δ

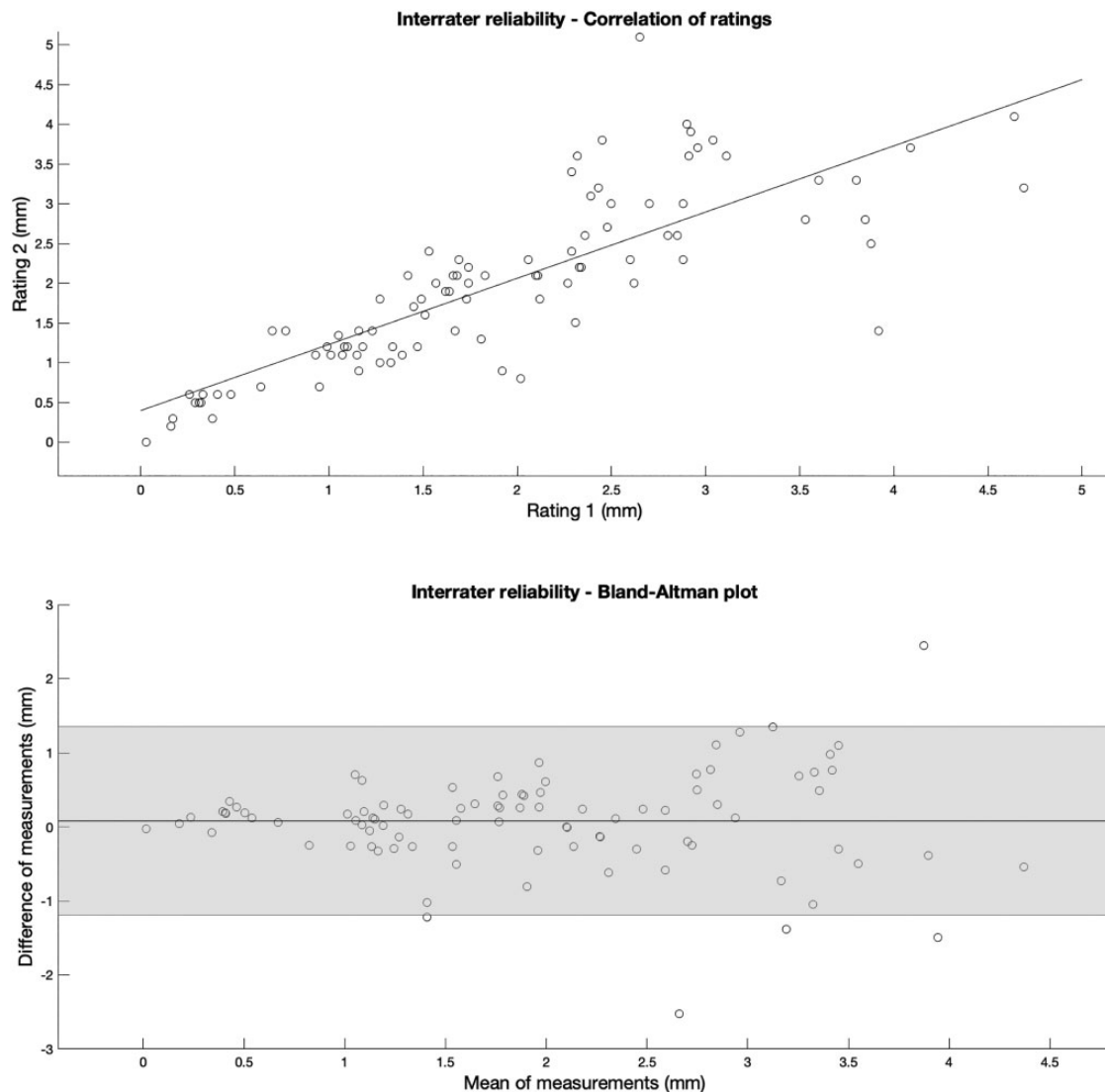


Figure 3. Correlation and Bland-Altman plots of interrater reliability. The horizontal line and gray area in the Bland-Altman plot show the mean difference in ratings and the respective 95% CI.

extrusion of 0.4 ± 0.6 mm and 0.3 ± 0.6 mm were measured for the injured and healthy knees, respectively. Differences between legs were nonsignificant ($t[18] = -0.264$; $P = .795$). It has to be mentioned that the small sample size may have weakened the statistical power of these results.

Clinical Findings and PROs

There were 2 patients who reported temporary blocking symptoms, and another 2 patients described pain during prolonged squatting. None of the participants reported limitations in activities of daily living. All patients were satisfied with the outcome, and all but 1 patient were able to return to their previous recreational sports level. No severe malalignment of the lower limb was detected. The clinical examination revealed positive signs for the medial meniscus in 1 patient only. No additional

pathological abnormalities were observed. The PRO scores acquired over the follow-up period are summarized in Table 2.

DISCUSSION

The most important findings of the present study are that lateral ME (1) decreased significantly after all-inside radial tear repair, (2) increased significantly (+21.8%) after load application, and (3) showed significantly higher values in the injured knee than in the noninjured knee. The nonsignificant difference in Δ extrusion between the healthy and injured knees suggests intact load acceptance behavior after lateral meniscal radial tear repair.

The high incidence of lateral meniscal tears associated with ACL injuries and the associated changes in knee joint biomechanics have led to increasing interest in meniscus-

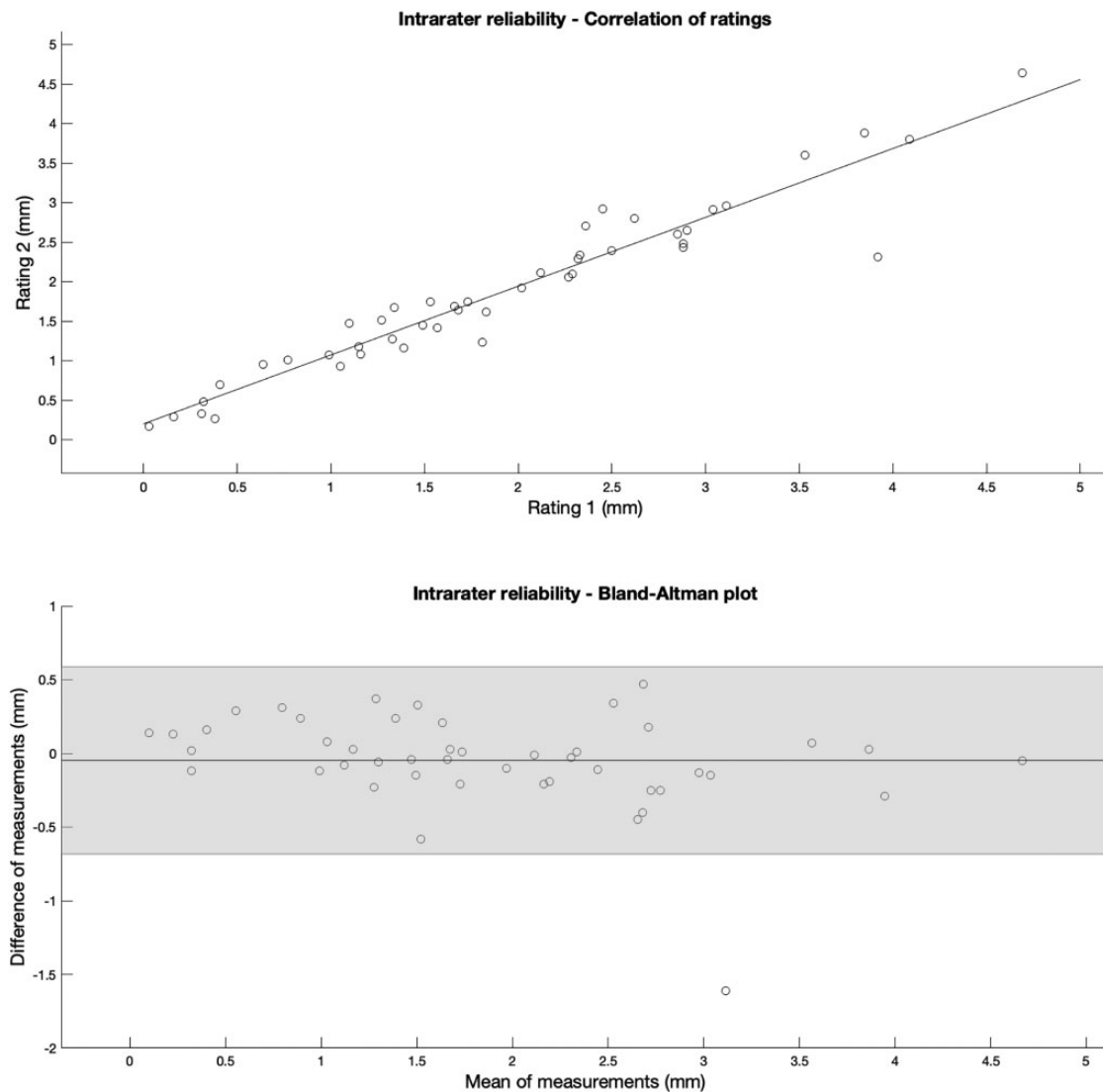


Figure 4. Correlation and Bland-Altman plots of intrarater reliability. The horizontal line and gray area in the Bland-Altman plot show the mean difference in ratings and the respective 95% CI.

preserving therapies. Hagino et al²² observed concomitant meniscal lesions in 79.2% of ACL-deficient knees. Tears of the lateral meniscus have been reported to occur in 69.4% of acute ACL injuries. Similarly, Fetzer et al¹⁷ detected more lateral meniscal lesions associated with ACL injuries than medial meniscal lesions, and radial tears accounted for >12% of the lateral meniscal lesions. Clinical research has indicated that radial tears account for 14% to 15% of all meniscal lesions.^{24,37} The high biomechanical effect of radial meniscal tears has been shown in 2 cadaveric studies.^{6,41} Ode et al⁴¹ detected significantly increased tibiofemoral contact pressure and a decreased contact area after radial transection of the lateral meniscus. In the same study, the mean tibiofemoral contact pressure after radial tear repair nearly reached that of an intact meniscus. According to Ode et al and Bedi et al,⁶ therapies preserving the lateral meniscus after radial tears are of crucial

biomechanical importance. The present study was performed to provide in vivo human data reflecting the efficacy of radial tear repair of the lateral meniscus. To our knowledge, this is the first study to investigate this issue using stress MRI mimicking a physiological setting.

ME is also evident in healthy participants. Boxheimer et al⁸ examined the changes in the meniscal position under different joint angles and loading conditions based on MRI of 22 asymptomatic volunteers. They detected radial displacement of the medial and lateral menisci in both the sagittal and coronal planes. The average extrusion in healthy volunteers was <3 mm and was more pronounced in the medial meniscus than in the lateral meniscus. Similar results were reported in clinical studies involving non-injured control groups.^{20,28,42} In the present study, the mean radial displacement of the lateral meniscus under nonweightbearing conditions was 1.0 ± 0.7 mm in the

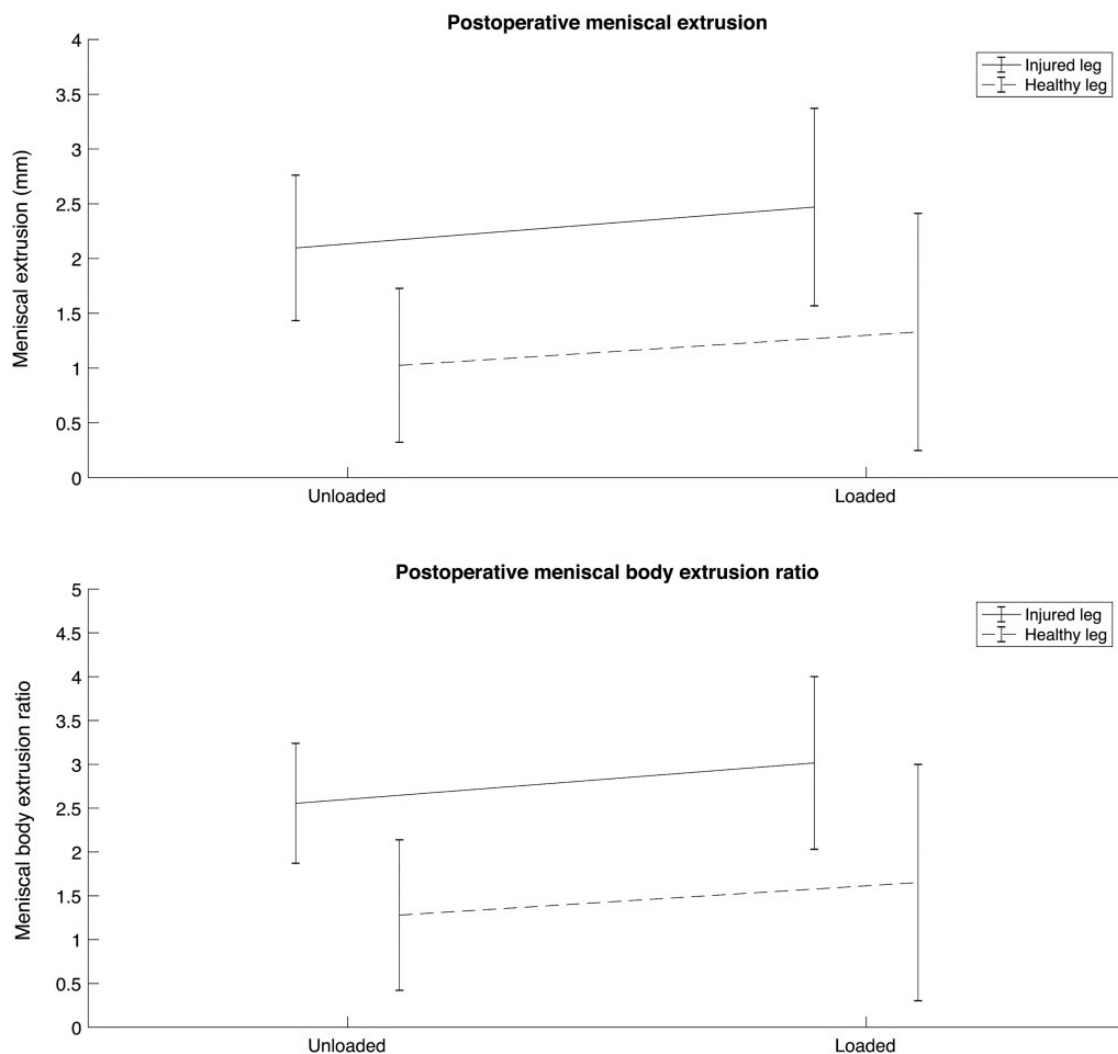


Figure 5. Mean postoperative meniscal extrusion (top) and meniscal body extrusion ratio (bottom) as measured in the unloaded and loaded conditions in the injured and noninjured legs (healthy). Error bars represent standard deviations.

TABLE 2
Patient-Reported Outcomes Before Injury, 6 and 12 Months Postoperatively, and at Last Follow-up^a

Measure	Before Injury	6 mo	12 mo	Last Follow-up
VAS for pain	0.7 ± 1.34	1.0 ± 1.00	1.3 ± 1.21	0.6 ± 0.84
Lysholm	92.2 ± 18.60	89.8 ± 7.79	88.3 ± 9.85	91.4 ± 7.89
Subjective IKDC	—	—	—	91.4 ± 6.71
KOOS Pain	—	—	—	95.6 ± 3.97
KOOS Symptoms	—	—	—	88.9 ± 10.44
KOOS Activities of Daily Living	—	—	—	99.6 ± 0.71
KOOS Sports and Recreation	—	—	—	94.5 ± 6.43
KOOS Quality of Life	—	—	—	80.6 ± 16.78
TAL, median (range)	7 (6-10)	6 (4-10)	6 (1-9)	6 (6-9)

^aData are shown as mean ± SD unless otherwise indicated. Dashes signify not reported. IKDC, International Knee Documentation Committee; KOOS, Knee Injury and Osteoarthritis Outcome Score; TAL, Tegner activity level; VAS, visual analog scale.

noninjured knee and 2.1 ± 0.6 mm in the injured knee. A threshold of 3 mm is often used to distinguish between physiological and pathological extrusion.^{20,28,36} At higher levels of extrusion, the meniscus is considered functionally ineffective. It should be noted, however, that physiological extrusion of menisci depends on several parameters, such as age and body mass index,^{1,15} and may be completely reversible.¹⁵ Therefore, the current fixed cut-off value is problematic. Consequently, no threshold value for pathological extrusion was defined in the present study. Extrusion of the healthy contralateral side served as a reference and was compared with that of the operated side.

The upright bipedal posture causes each knee joint to be loaded with approximately 50% of a patient's body weight. Because of the composition and cross section of the meniscus, this axial force leads to a change in its position. The increase of ME in a loaded condition is defined as dynamic ME.^{1,15,30} Thus, in contrast to standard MRI, the application of different loading conditions allows for ME to be studied under conditions that are similar to physiological demands. Numerous studies have shown a significant increase in radial displacement of the menisci when an axial load is applied to the joint.^{1,8,15,42} However, few studies have dynamically investigated ME with the use of MRI.^{8,9,42,48} These investigations, however, have shown some limitations regarding the reproducibility of knee positioning and consistent load application. In the present study, a newly designed nonferromagnetic pneumatic knee brace was used for standard leg positioning and load application during MRI. Using the control panel, it was possible to apply precisely 50% of the body weight as an axial force via the pneumatic system. Based on this method, a significant increase in ME from 1.6 ± 0.9 mm to 1.9 ± 1.1 mm (+21.8%; $P = .029$) was induced with load application.

Several studies have indicated the dynamic behavior of the menisci.^{1,8,9,15,30,42,48,50} A recent study showed that the dynamic increase of medial ME is significantly compromised in the presence of a complete medial root tear compared with the healthy state (mean Δ extrusion, 0.1 ± 0.2 mm [study group] vs 1.0 ± 0.4 mm [control group]).³⁰ This phenomenon is called the "dead meniscus sign"³⁰ and may be attributable to an interruption in the ring structure and potentially associated impairment of the viscoelasticity of meniscal tissue. In the present study, the difference in the mean Δ extrusion between the healthy (0.3 ± 0.6 mm) and injured (0.4 ± 0.6 mm) knees was small and statistically nonsignificant ($P = .795$). Moreover, the condition \times leg interaction was nonsignificant, suggesting that the compression-associated increase in ME did not differ significantly between the injured and healthy knees. It is therefore assumed that the dynamic behavior of the lateral meniscus is still maintained after radial tear repair. Mean lateral ME under nonweightbearing conditions was 1.0 ± 0.7 mm and 2.1 ± 0.6 mm for the noninjured and injured knee, respectively ($t[9]$, 2.262; $P = .002$). For the weight-bearing conditions, mean lateral ME was 1.3 ± 1.1 mm and 2.5 ± 0.9 mm for the noninjured and injured knee, respectively ($t[9]$, 2.262; $P = .002$).

Ichiba and Makuya²⁸ showed a significant progression of lateral ME from 1.8 mm preoperatively to 2.4 mm

postoperatively after ACL reconstruction. It should be mentioned that meniscus-preserving therapy was only performed in 3 of the 32 cases with concomitant meniscal lesions. The authors demonstrated that radial displacement of the lateral meniscus depends on the size and kind of the tear. In the present study, all-inside radial tear repair in the posterior horn of the lateral meniscus reduced unloaded ME by 32.4% (preoperative: 3.2 ± 1.1 mm; postoperative: 2.1 ± 0.6 mm). From a clinical point of view, this significant ($P = .033$) finding represents a mean decrease of extrusion of 1.1 mm. However, it should be mentioned that excessive joint effusion in the acute condition at the time of preoperative MRI could temporarily increase ME because of increased intra-articular pressure.

Pula et al⁴⁴ detected 0.5 ± 0.72 mm of lateral ME in patients with an isolated ACL injury compared with 0.8 ± 0.94 mm in those with an additional posterior lateral meniscus root tear. This difference was not significant and may have been related to the occurrence of MFLs, which were arthroscopically confirmed in all patients. The presence of MFLs has a stabilizing effect on the lateral meniscus.¹⁸ In this study, patients with posterior lateral meniscus root tears were excluded; thus, bias due to the described¹⁸ stabilizing effect of the MFLs is unlikely.

Limitations

The current study has some limitations. The small sample size may have weakened the statistical power of the results and, therefore, prevents generalization to large populations. The included injury pattern is rare, and the need for an unaffected contralateral knee resulted in the exclusion of many potential participants. Moreover, all preoperative MRI scans were acquired in a supine, unloaded position. Consequently, the comparison between preoperative and postoperative ME could only be performed in the conditions without axial load application. In addition, because of the small sample size, no correlation analysis could be performed regarding possible confounding factors, such as body mass index or pre-existing cartilage damage.

CONCLUSION

In summary, the present study provided the following evidence:

- All-inside radial tear repair in the posterior horn of the lateral meniscus led to a significant reduction in lateral ME from preoperative levels.
- Loading the knee at 50% of the body weight led to a significant increase (+21.8%) in lateral ME.
- Irrespective of the loading condition, significantly higher values (+93.2%) of lateral ME were observed in the injured knee. However, the difference in Δ extrusion between the healthy and injured knees was nonsignificant.

Based on these findings, we conclude that all-inside radial tear repair of the lateral meniscus may help to preserve the

dynamic behavior of the lateral meniscus, thus reducing biomechanical stress acting on the adjacent cartilage.

ACKNOWLEDGMENT

The authors acknowledge the support of CT and MRT Betreibergesellschaft Hochrum and the help of the radiology technicians at Privatklinik Hochrum.

REFERENCES

- Achtnich A, Petersen W, Willinger L, et al. Medial meniscus extrusion increases with age and BMI and is depending on different loading conditions. *Knee Surg Sports Traumatol Arthrosc.* 2018;26(8):2282-2288.
- Anderson L, Watts M, Shapter O, et al. Repair of radial tears and posterior horn detachments of the lateral meniscus: minimum 2-year follow-up. *Arthroscopy.* 2010;26(12):1625-1632.
- Andersson-Molina H, Karlsson H, Rockborn P. Arthroscopic partial and total meniscectomy: a long-term follow-up study with matched controls. *Arthroscopy.* 2002;18(2):183-189.
- Arnoczky SP, Warren RF. Microvasculature of the human meniscus. *Am J Sports Med.* 1982;10(2):90-95.
- Baratz ME, Fu FH, Mengato R. Meniscal tears: the effect of meniscectomy and of repair on intraarticular contact areas and stress in the human knee. A preliminary report. *Am J Sports Med.* 1986;14(4):270-275.
- Bedi A, Kelly N, Baad M, et al. Dynamic contact mechanics of radial tears of the lateral meniscus: implications for treatment. *Arthroscopy.* 2012;28(3):372-381.
- Blyth M, Anthony I, Francq B, et al. Diagnostic accuracy of the Thesaly test, standardised clinical history and other clinical examination tests (Apley's, McMurray's and joint line tenderness) for meniscal tears in comparison with magnetic resonance imaging diagnosis. *Health Technol Assess.* 2015;19(62):1-62.
- Boxheimer L, Lutz AM, Treiber K, et al. MR imaging of the knee: position related changes of the menisci in asymptomatic volunteers. *Invest Radiol.* 2004;39(5):254-263.
- Boxheimer L, Lutz AM, Zanetti M, et al. Characteristics of displaceable and nondisplaceable meniscal tears at kinematic MR imaging of the knee. *Radiology.* 2006;238(1):221-231.
- Braun S, Vogt S, Imhoff AB. Stage oriented surgical cartilage therapy: current situation [In German]. *Orthopade.* 2007;36(6):589-599, quiz 600.
- Brody JM, Lin HM, Hulstyn MJ, Tung GA. Lateral meniscus root tear and meniscus extrusion with anterior cruciate ligament tear. *Radiology.* 2006;239(3):805-810.
- Choi NH, Kim TH, Son KM, Victoroff BN. Meniscal repair for radial tears of the midbody of the lateral meniscus. *Am J Sports Med.* 2010;38(12):2472-2476.
- Cinque ME, Geeslin AG, Chahla J, Dornan GJ, LaPrade RF. Two-tunnel transtibial repair of radial meniscus tears produces comparable results to inside-out repair of vertical meniscus tears. *Am J Sports Med.* 2017;45(10):2253-2259.
- Costa CR, Morrison WB, Carrino JA. Medial meniscus extrusion on knee MRI: is extent associated with severity of degeneration or type of tear? *AJR Am J Roentgenol.* 2004;183(1):17-23.
- Diermeier T, Beitzel K, Bachmann L, et al. Mountain ultramarathon results in temporary meniscus extrusion in healthy athletes. *Knee Surg Sports Traumatol Arthrosc.* 2019;27(8):2691-2697.
- Dunlap WP, Cortina JM, Vaslow JB, Burke MJ. Meta-analysis of experiments with matched groups or repeated measures designs. *Psychological Methods.* 1996;1(2):170-177.
- Fetzer GB, Spindler KP, Amendola A, et al. Potential market for new meniscus repair strategies: evaluation of the MOON cohort. *J Knee Surg.* 2009;22(3):180-186.
- Forkel P, Herbolt M, Schulze M, et al. Biomechanical consequences of a posterior root tear of the lateral meniscus: stabilizing effect of the meniscofemoral ligament. *Arch Orthop Trauma Surg.* 2013;133(5):621-626.
- Fox AJ, Wanivenhaus F, Burge AJ, Warren RF, Rodeo SA. The human meniscus: a review of anatomy, function, injury, and advances in treatment. *Clin Anat.* 2015;28(2):269-287.
- Gale DR, Chaisson CE, Totterman SM, Schwartz RK, Gale ME, Felson D. Meniscal subluxation: association with osteoarthritis and joint space narrowing. *Osteoarthritis Cartilage.* 1999;7(6):526-532.
- Garrett WE Jr, Swiontkowski MF, Weinstein JN, et al. American Board of Orthopaedic Surgery Practice of the Orthopaedic Surgeon, part-II: certification examination case mix. *J Bone Joint Surg Am.* 2006;88(3):660-667.
- Hagino T, Ochiai S, Senga S, et al. Meniscal tears associated with anterior cruciate ligament injury. *Arch Orthop Trauma Surg.* 2015;135(12):1701-1706.
- Haklar U, Kocaoglu B, Nalbantoglu U, Tuzuner T, Guven O. Arthroscopic repair of radial lateral meniscus [corrected] tear by double horizontal sutures with inside-outside technique. *Knee.* 2008;15(5):355-359.
- Harper KW, Helms CA, Lambert HS III, Higgins LD. Radial meniscal tears: significance, incidence, and MR appearance. *AJR Am J Roentgenol.* 2005;185(6):1429-1434.
- Hinman RS, May RL, Crossley KM. Is there an alternative to the full-leg radiograph for determining knee joint alignment in osteoarthritis? *Arthritis Rheum.* 2006;55(2):306-313.
- Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med.* 2000;30(1):1-15.
- Hoser C, Fink C, Brown C, Reichkender M, Hackl W, Bartlett J. Long-term results of arthroscopic partial lateral meniscectomy in knees without associated damage. *J Bone Joint Surg Br.* 2001;83(4):513-516.
- Ichiba A, Makuya K. Radial displacement of the lateral meniscus before and after anterior cruciate ligament reconstruction. *Arch Orthop Trauma Surg.* 2012;132(3):321-327.
- Jackson JP. Degenerative changes in the knee after meniscectomy. *Br Med J.* 1968;2(5604):525-527.
- Karpinski K, Diermeier T, Willinger L, Imhoff AB, Achtnich A, Petersen W. No dynamic extrusion of the medial meniscus in ultrasound examination in patients with confirmed root tear lesion. *Knee Surg Sports Traumatol Arthrosc.* 2019;27(10):3311-3317.
- Keene GC, Bickerstaff D, Rae PJ, Paterson RS. The natural history of meniscal tears in anterior cruciate ligament insufficiency. *Am J Sports Med.* 1993;21(5):672-679.
- Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med.* 2016;15(2):155-163.
- Lerer DB, Umans HR, Hu MX, Jones MH. The role of meniscal root pathology and radial meniscal tear in medial meniscal extrusion. *Skeletal Radiol.* 2004;33(10):569-574.
- Lutz C, Dalmay F, Ehkirch FP, et al. Meniscectomy versus meniscal repair: 10 years radiological and clinical results in vertical lesions in stable knee. *Orthop Traumatol Surg Res.* 2015;101(8)(suppl):S327-S331.
- Maffulli N, Longo UG, Campi S, Denaro V. Meniscal tears. *Open Access J Sports Med.* 2010;1:45-54.
- Magee T. MR findings of meniscal extrusion correlated with arthroscopy. *J Magn Reson Imaging.* 2008;28(2):466-470.
- Magee T, Shapiro M, Williams D. MR accuracy and arthroscopic incidence of meniscal radial tears. *Skeletal Radiol.* 2002;31(12):686-689.
- Masouros SD, McDermott ID, Amis AA, Bull AM. Biomechanics of the meniscus-meniscal ligament construct of the knee. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(12):1121-1132.
- Moulton SG, Bhatia S, Civitaresse DM, Frank RM, Dean CS, LaPrade RF. Surgical techniques and outcomes of repairing meniscal radial tears: a systematic review. *Arthroscopy.* 2016;32(9):1919-1925.

40. Navali AM, Bahari LA, Nazari B. A comparative assessment of alternatives to the full-leg radiograph for determining knee joint alignment. *Sports Med Arthrosc Rehabil Ther Technol*. 2012;4(1):40.
41. Ode GE, Van Thiel GS, McArthur SA, et al. Effects of serial sectioning and repair of radial tears in the lateral meniscus. *Am J Sports Med*. 2012;40(8):1863-1870.
42. Patel R, Eltgroth M, Souza R, et al. Loaded versus unloaded magnetic resonance imaging (MRI) of the knee: effect on meniscus extrusion in healthy volunteers and patients with osteoarthritis. *Eur J Radiol Open*. 2016;3:100-107.
43. Petty CA, Lubowitz JH. Does arthroscopic partial meniscectomy result in knee osteoarthritis? A systematic review with a minimum of 8 years' follow-up. *Arthroscopy*. 2011;27(3):419-424.
44. Pula DA, Femia RE, Marzo JM, Bisson LJ. Are root avulsions of the lateral meniscus associated with extrusion at the time of acute anterior cruciate ligament injury? A case control study. *Am J Sports Med*. 2014;42(1):173-176.
45. Ra HJ, Ha JK, Jang SH, Lee DW, Kim JG. Arthroscopic inside-out repair of complete radial tears of the meniscus with a fibrin clot. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(9):2126-2130.
46. Salata MJ, Gibbs AE, Sekiya JK. A systematic review of clinical outcomes in patients undergoing meniscectomy. *Am J Sports Med*. 2010;38(9):1907-1916.
47. Song HS, Bae TY, Park BY, Shim J, In Y. Repair of a radial tear in the posterior horn of the lateral meniscus. *Knee*. 2014;21(6):1185-1190.
48. Stehling C, Souza RB, Hellio Le Graverand MP, et al. Loading of the knee during 3.0 T MRI is associated with significantly increased medial meniscus extrusion in mild and moderate osteoarthritis. *Eur J Radiol*. 2012;81(8):1839-1845.
49. Stein T, Mehling AP, Welsch F, von Eisenhart-Rothe R, Jager A. Long-term outcome after arthroscopic meniscal repair versus arthroscopic partial meniscectomy for traumatic meniscal tears. *Am J Sports Med*. 2010;38(8):1542-1548.
50. Vedi V, Williams A, Tennant SJ, Spouse E, Hunt DM, Gedroyc WM. Meniscal movement: an in-vivo study using dynamic MRI. *J Bone Joint Surg Br*. 1999;81(1):37-41.
51. Wu IT, Hevesi M, Desai VS, et al. Comparative outcomes of radial and bucket-handle meniscal tear repair: a propensity-matched analysis. *Am J Sports Med*. 2018;46(11):2653-2660.
52. Zhang F, Kumm J, Svensson F, Turkiewicz A, Frobell R, Englund M. Risk factors for meniscal body extrusion on MRI in subjects free of radiographic knee osteoarthritis: longitudinal data from the Osteoarthritis Initiative. *Osteoarthritis Cartilage*. 2016;24(5):801-806.