Original Article

Steep Posterior Tibial Slope and Excessive Anterior Tibial Translation Are Associated With Increased Sagittal Meniscal Extrusion After Posterior Lateral Meniscus Root Repair Combined With Anterior Cruciate Ligament Reconstruction

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Purpose: To (1) evaluate the clinical and radiographic outcomes of patients with primary anterior cruciate ligament reconstruction (ACLR) with type II posterior lateral meniscus root tear (PLMRT) repair and (2) identify whether increased anterior tibial subluxation of the lateral compartment (ATSLC) and steeper posterior tibial slope (PTS) are associated with sagittal lateral meniscal extrusion (LME). **Methods:** Patients who underwent primary anatomic ACLR with concomitant type II PLMRTs using the all-inside side-to-side repair technique between November 2014 and September 2020 were identified. To be included, patients must have had a minimum of 2 years follow-up. All patients, including those with ATSLC and PTS and sagittal and coronal LME, were retrospectively reviewed clinically and radiologically. The patients were divided into 2 subgroups according to the occurrence of sagittal LME. **Results:** Forty patients were included in this study with a mean follow-up of 44 months (range, 24-94 months). In general, the postoperative parameters, including grade of pivot shift, side-to-side difference, ATSLC, Lysholm score, and International Knee Documentation Committee (IKDC) score, were significantly improved compared with the preoperative ones. However, postoperative sagittal LME was detected to be significantly larger than the preoperative one. Minimal clinically important difference (MCID) analysis for postoperative outcomes showed that the rate of patients who achieved MCID thresholds was 100% for Lysholm, 95% for IKDC, 42.50% for coronal LME, 62.50% for sagittal LME, 40% for ATSLC, and 100% for side-to-side difference. Further comparisons, where patients were divided into 2 subgroups according to the occurrence of sagittal LME, showed significant differences in PTS, ATSLC, and coronal LME. **Conclusions:** Clinical outcomes after type II PLMRT repair with primary ACLR were significantly improved, except for LME, at the 2-year postoperative follow-up. After repair of type II PLMRT injuries, the presence of sagittal LME was associated with increased PTS and ATSLC. **Level of Evidence:** Level III, retrospective cohort study.

Posterior lateral meniscus root tears (PLMRTs) are concomitant injuries of anterior cruciate ligament (ACL) tears, with a reported incidence of 7% to 12%.[1] PLMRTs significantly alter the biomechanics and kinematics of the knee joint, resulting in increased tibiofemoral contact pressure,[2,3] and increase the internal rotational as well as the anterior shift instability in an intact ACL knee. Many PLMRT repair techniques

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have been recorded.[4] Meniscal repairs have a high rate of healing when performed during primary ACL reconstruction (ACLR) or ACLR revision.[5,6] A side-to-side repair technique was described, which showed satisfactory clinical outcomes in follow-up at a mean of 30.7 months.[7]

Lateral meniscal extrusion (LME) has been reported in patients with posterior root tear or radial tear[8] and as a complication in meniscus transplantation.[9] Meniscal extrusion leads to meniscal dysfunction and results in increased tibiofemoral contact pressures and decreased contact areas in the lateral compartment.[10] Previous study reported that the displaced lateral meniscus was reduced in the coronal plane after repair of PLMRTs.[3,11] However, Tsujii et al.[6] described that sagittal extrusion of the lateral meniscus on magnetic resonance imaging (MRI) was significantly larger among the patients who underwent repair of PLMRTs combined with ACLR. It is unclear why LME is aggravated in the sagittal plane and whether leg alignment correlates with meniscal subluxation.

There is an increasing number of studies on the anatomic features of the proximal tibia, especially a steep posterior tibial slope (PTS), either lateral[12,13] or medial,[14] influencing the biomechanics of the tibiofemoral joint with respect to an increase in anterior tibial translation, ACL loading, and tibial shear force.[12-14] The posterior root and horn of the lateral meniscus, acting as a rotational knee stabilizer in pivoting action,[15-18] may also be affected by increased PTS.[19] However, the relationship between PTS and meniscal extrusion after repair of PLMRTs remains unclear.

The position of the tibia relative to the femur has been reported to be dramatically altered in ACL-unstable knees by Almekinders and colleagues[20-22] in their consecutive studies, where a significant anterior tibial subluxation (ATS) was found in lax ACL graft patients in X-ray radiographs. Further, Tanaka et al.[23] reported that the anterior tibial subluxation of the lateral compartment (ATSLC) was a significant factor that influenced the outcomes of ACLR using MRI evaluation. In addition, McDonald et al.[24] also reported that failed ACLR was associated with an increased ATS, which was related to an injury of secondary knee stabilizers, especially the lateral and medial menisci. Zheng et al.[25] proved that concomitant PLMRT after ACL injuries could further increase ATSLC because of the deprivation of the "wedge effect" maintained by the posterior root of lateral meniscus. These studies have raised attention to the importance of a normal tibiofemoral position in ACLR, where the ATSLC and PLMRT could negatively affect the restoration of knee kinematics and the improvement of knee stability.

Given the indispensable function of the menisci in maintaining stable knee joint mechanics, we were interested to investigate what role factors such as PTS and ATSLC would play in influencing meniscal extrusion postoperatively. The purposes of the study are to (1) evaluate the clinical and radiographic outcomes of patients with primary ACLR with type II PLMRT repair and (2) identify whether increased ATSLC and steeper PTS are associated with sagittal lateral meniscal extrusion (sLME). We hypothesized that sLME is aggravated and that the presence of postoperative sLME would be associated with increased PTS and ATSLC.

Methods

From November 2014 to September 2020, patients diagnosed with ACL injury who underwent primary ACLR in our department were retrospectively reviewed, and those who were diagnosed with complete ACL rupture and concomitant type II PLMRTs were enrolled in this study ($n = 40$).[26] Patients who met 1 or more of the following criteria were excluded: (1) partial ACL rupture; (2) any tear in the lateral meniscus, except for type II PLMRTs (type II PLMRTs were defined as a radial tear near the root attachment [<9 mm] with an intact meniscofemoral ligament)[26,27]; (3) skeletal immaturity; (4) time from injury to surgery for more than 12 weeks; (5) a history of surgery in the ipsilateral knee; (6) the presence of posterior cruciate ligament injury, posterolateral corner injury, or grade 2 to 3 collateral ligament injuries; (7) mild to severe coronal-plane lower limb malalignment (>5° varus/valgus malalignment); (8) generalized joint laxity (>5 of 9 on the Beighton score) or significant local hyperextension (>10°) in the affected knee joint; and (9) the lack of MRI examinations at our hospital, both preoperatively and at least 2 years postoperatively. All study protocols were approved by the ethics board of our hospital (ID: SYSEC-KY-KS-001), and informed consent was obtained from all study participants.

Surgical Techniques

All patients underwent single-bundle ACLR with 4- to 6-strand hamstring tendon autografts by a senior surgeon (W.-P.L.). The reconstruction surgery was performed using an independent femoral tunnel drilling technique as indicated in a previous research report.[28] The graft was fixed with an Endobutton CL (Smith & Nephew Endoscopy) and an absorbable bio-interference screw (Smith & Nephew Endoscopy).

For type II PLMRT patients, H-plasty suture repair was performed to fix the tear ends of the lateral meniscus root. The technique was performed as previously described.[3,7] Briefly, a FasT-Fix device (Smith & Nephew) was used to treat the radial tear with side-to-side suturing. The first suture bar anchor was delivered into the root remnant, with an average depth of 12 to 14 mm, and the other one was inserted across the tear area at the opposite end of the meniscus at the same

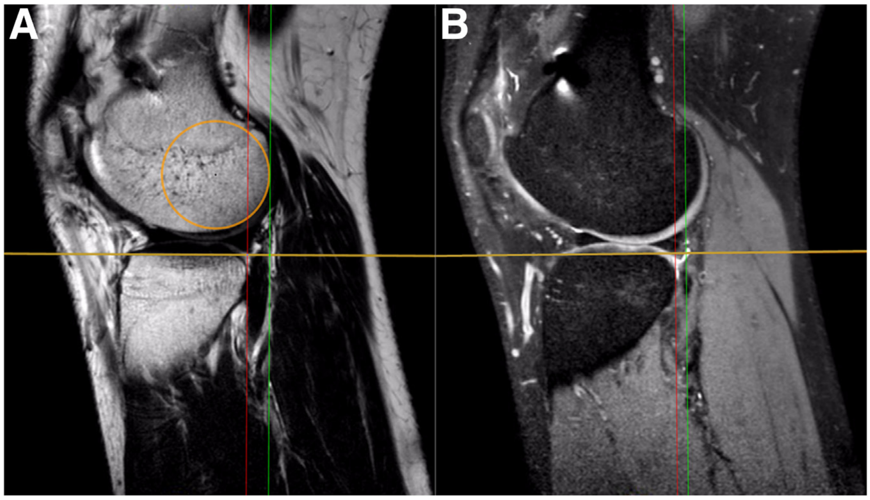

Fig 1. The procedures of anterior tibial subluxation of the lateral compartment (ATSLC) and sagittal lateral meniscal extrusion (sLME) measurement. (A) According to the measurement protocol of McDonald et al.,[24] magnetic resonance imaging (MRI) with T1 sequence is chosen first, which is defined as the most medial image of the fibula head at the tibiofibular joint. The yellow circle represents a best-fit circle over the posterior femoral condyle at the subchondral bone. A yellow line is drawn representing the lateral tibial plateau. A green line perpendicular to the yellow line and tangent to the yellow circle is drawn. An additional red line perpendicular to the yellow line and tangent to the posterior margin of the tibial plateau is also drawn. The distance between the green line and the red line represents the ATSLC. (B) The sLME is measured with the same section of MRI with the PDW_SPAIR sequence. A yellow line is drawn representing the lateral tibial plateau. A red line perpendicular to the yellow line and tangent to the posterior margin of the tibial plateau is drawn. A green line perpendicular to the yellow line and tangent to the posterior margin of the lateral meniscus is also drawn. The sLME was defined as the distance between the green line and the red line.

depth. The suture was tightened slightly to ensure that the distal part of the tear was closed to the root insertion. Next, another FasT-Fix device was used for vertical suturing in the root part in a bottom-to-top or top-to-bottom manner, and the distal part of the tear was treated using a similar method with a third suture device. Finally, the knot of the first side-to-side suture was completely tightened to closely integrate the distal part of the tear, the remaining root, and the joint capsule of the lateral meniscus.

Postoperative Rehabilitation

All patients underwent a stepwise rehabilitation protocol. Nonweightbearing was required for 4 weeks, and full weightbearing was allowed from week 6 postoperatively. Knee flexion from 0° to 90° was performed from weeks 1 to 4 postoperatively. Daily activities and jogging were not allowed until 3 months after surgery. Competitive sports were permitted 10 to 12 months after surgery.

Radiologic Measurement

MRI scans were obtained at the follow-up time of 2 years at least postoperatively using a 3.0-T MRI scanner (Philips). During the examination, each patient was supine in a relaxed position with the knee fully extended and 15° of external rotation.

Measurements of ATSLC were divided into 3 steps according to McDonald et al.[24] (Fig 1A). First, on T1-weighted sagittal sequences, a scan showing the most medial image of the fibula head at the tibiofibular joint was identified. After the tangent line of the lateral plateau of the tibia was drawn, the most suitable circle was delineated at the subchondral line of the posterior border of the lateral condyle of the femur. Then, 2 parallel lines perpendicular to the lateral tibial plateau were determined to measure the subluxation. The first line was tangent to the circle of the posterior border of the lateral femoral condyle when the second line intersected the posterior edge of the tibial plateau. Third, the distance between the 2 lines was surveyed as the ATSLC.

Measurements of sLME were performed on the same slice measuring ATSLC (Fig 1B).[29] The first line was drawn to pass through the most posterior margin of the tibial plateau, and the second line was drawn to be tangent to the most posterior aspect of the posterior horn of the lateral meniscus. Both lines were parallel to the tibia, and sLME was measured as the distance

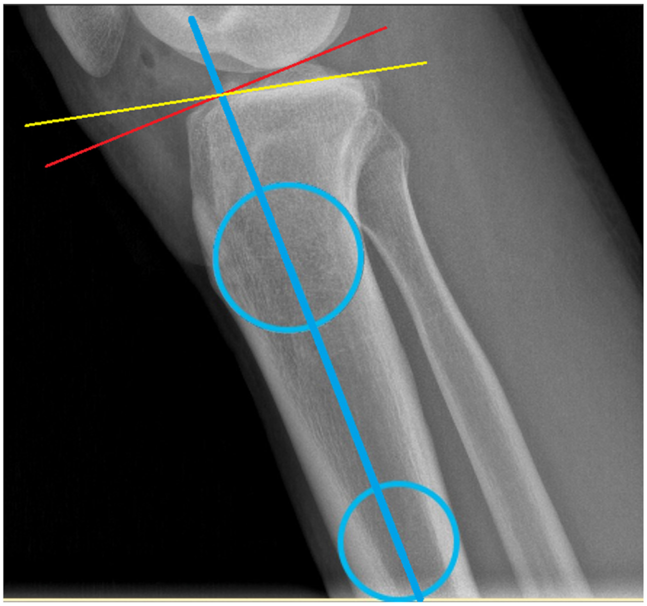

Fig 2. The procedures of posterior tibial slope (PTS) measurement. Two circles tangent to the anterior and posterior tibial cortices were drawn. The line connecting the centers of the 2 circles was defined as the tibial longitudinal axis (blue line). Then a line perpendicular to the longitudinal axis was drawn (red line). A tangent to the lateral tibial plateau cortices was drawn (yellow line). The PTS was defined as the angle between the yellow and the red lines.

between the 2 lines. The central sagittal slice was selected from a PDW_SPAIR sequence (Fig 1). Coronal lateral meniscal extrusion (cLME) was surveyed on coronal knee MRI from the lateral tibial border to the lateral margin of the meniscal body as previously described.[7]

The PTS was measured on the lateral knee x-ray radiograph (Fig 2). By measuring the angle between a proximal anatomic axis of the tibia and the line drawn tangentially to the tibial plateau, the value of PTS was identified. The proximal anatomic axis was drawn with a line connecting the midcortical diameters of the tibia at a point 5 cm and 15 cm distal to the joint line.[30] Two observers calculated the mean value. The abnormal value of the PTS has been defined as above 10.0° according to a previous study on Chinese patients.[31]

All measurements were performed by 2 orthopaedic surgeons (Z.-Z.Z., H.-Z.Z.) using a picture archiving and communication system workstation (GE Healthcare). The intraclass correlation coefficient (ICC) was calculated by randomly selecting patients to determine the reproducibility. ICC values >0.9 were considered excellent, and values between 0.8 and 0.9 were considered good.[32] Two blinded observers measured both the PTS and sLME, and 1 measured all selected

Table 1. Comparisons Between Preoperative and Final Follow-Up Clinical Outcomes

Characteristic	Preoperatively (n = 40)	Final Follow-up (n = 40)	*P* Value
Grade of pivot-shift test, n			.00*
Low grade (grades 0 and 1)	8	35	
High grade (grades 2 and 3)	32	5	
Associated injury, n			
Medial meniscus injury	28	0	.00*
KNEELAX arthrometer side-to-side difference, mm	8.04 [7.07, 8.77]	2.39 [2.24, 2.61]	.00*
Static ATSLC, mm	6.00 [5.60, 5.45]	5.35 [3.70, 6.85]	.01*
Coronal meniscal extrusion, mm	0.95 [0, 1.95]	0 [0, 2.00]	.56
Sagittal meniscal extrusion, mm	1.60 [1.15, 1.80]	2.50 [1.15, 2.90]	.01*
Lysholm score	60.00 [53.00, 70.50]	91.00 [89.00, 92.00]	.00*
IKDC score	55.50 [50.00, 60.50]	86.50 [83.00, 90.00]	.00*

NOTE. Values are presented as median [quartile] unless otherwise indicated.

ATSLC, anterior tibial subluxation of the lateral compartment; IKDC, International Knee Documentation Committee.

*Statistically significant ($P < .05$).

patients twice, the other 1 month apart. The interobserver and intraobserver ICCs for the PTS measurement were 0.9 and 0.91, and the values of ICCs for sLME were 0.9 and 0.9, respectively.

Data Collection

Preoperative information, including demographic data (age, sex, body mass index, time from injury to surgery, and injury side), physical examination results (the pivot-shift test and KNEELAX arthrometer side-to-side difference [SSD]), radiologic results (ATSLC, cLME, sLME, and PTS), clinical scores (Lysholm score and International Knee Documentation Committee [IKDC] score), and intraoperative findings (associated medial meniscus injury) were collected.

Postoperative data, including follow-up time, physical examination results (the pivot-shift test and KNEELAX arthrometer SSD), radiographic results (ATSLC, sLME, and cLME were evaluated by MRI, whereas PTS was evaluated by x-ray), and clinical

Table 2. MCID Analysis of Postoperative Clinical Outcomes

	All (n = 40)		
Characteristic	Δ, Mean (SD)	MCID	Δ ≥ MCID, n (%)
Lysholm	29.08 (10.88)	5.44	40 (100.00)
IKDC	29.80 (9.20)	4.60	38 (95.00)
cLME	−0.17 (1.52)	0.76	17 (42.50)
sLME	0.62 (1.31)	0.66	25 (62.50)
ATSLC	−1.38 (2.67)	1.34	16 (40.00)
SSD	−5.54 (1.06)	0.53	40 (100.00)

NOTE. Δ indicates the change between postoperative and preoperative score of certain outcome measure

ATSLC, anterior tibial subluxation of the lateral compartment; cLME, lateral meniscal extrusion; IKDC, International Knee Documentation Committee; sLME, sagittal lateral meniscal extrusion; SSD, side-to-side difference.

scores (Lysholm and IKDC scores) at final follow-up were collected. All patients underwent second-look arthroscopy postoperatively, and the repair integrity of the meniscus was evaluated by second-look arthroscopy using the criteria advocated by Miao et al.[33] Repaired menisci that met all the criteria were considered completely healed, while repaired menisci that did not meet one of the criteria were considered unhealed.

Statistical Analyses

Statistical analyses were performed using SPSS (version 25; SPSS, Inc.). Continuous variables were reported as median [quartile], and categorical variables were reported as frequency (percentage). The normality of the data has been tested. Paired chi-square test or paired rank-sum test was performed for comparisons of the preoperative and postoperative data of all patients. For comparisons between the sLME group and non-sLME group, rank-sum test or Fisher exact test was performed, and for comparisons with each group, paired rank-sum test or paired chi-square test was performed. Minimal clinically important difference (MCID) was ascertained with a distribution-based method by calculating 50% of the standard deviation (SD) for change between preoperative and postoperative outcomes.

For all the analyses, statistical significance level was set at $P < .05$.

Results

Clinical Assessment and Demographic Data

The pre- and postoperative results of clinical assessment for all patients are compared and summarized in Table 1. There were 40 patients eligible with ACL + PLMRT injuries for analysis with a mean follow-up of 44 months (range, 24-94 months). The second-look arthroscopy was performed at a mean 17.5 months (range, 14-19 months). Results of final follow-up showed significant improvement, including grade of pivot shift, SSD, ATSLC, Lysholm score, and IKDC score. However, no significant change has been observed regarding the overall average cLME (0.95 mm preoperatively vs 0 mm postoperatively, $P = .56$), with the overall average sLME dramatically enlarged postoperatively (1.60 mm preoperatively vs 2.50 mm postoperatively, $P = .01$). In specific, the results of postoperative MRI showed that 32 patients demonstrated sLME, while 8 patients had no sLME (non-sLME) at final follow-up. In Table 2, the distribution-based MCIDs for Lysholm, IKDC, cLME, sLME, ATSLC, and SSD were calculated to be 5.44, 4.60, 0.76, 0.66, 1.34 ,and 0.53, respectively. The rate of patients who achieved MCID thresholds was 100% for Lysholm, 95% for IKDC, 42.50% for cLME, 62.50% for sLME, 40% for ATSLC, and 100% for SSD. The preoperative demographic statistics are summarized in Table 3. There were no differences between the 2 groups in preoperative data, except for the PTS degree. The median PTS in the sLME group was significantly larger than that in the non-sLME group (11.8° vs 10.2°, respectively; $P = .042$).

Table 3. Patient Characteristics in the sLME Group and the Non-sLME Group

Characteristic	sLME (n = 32)	Non-sLME (n = 8)	*P* Value	Power
Age, y	26.00 [21.00, 31.25]	27.00 [23.75, 28.50]	.906	
Sex				
Male	27 (84.4)	7 (87.5)	1.000	
Female	5 (15.6)	1 (12.5)		
BMI	22.75 [21.48, 24.29]	23.96 [23.42, 25.06]	.101	
Time from injury to surgery, wk	2.00 [2.00, 6.00]	2.50 [2.00, 4.25]	.945	
Injury side, n				
Left	13 (40.6)	2 (25.0)	.686	
Right	19 (59.4)	6 (75.0)		
Posterior tibial slope	11.80 [10.47, 13.65]	10.20 [9.80, 10.80]	.042*	0.708

NOTE. Values are presented as median [quartile] or number (%) unless otherwise indicated.

*Statistically significant ($P < .05$).

Table 4. Comparisons of Results for Pre- and Postoperative Assessments Between the sLME Group and the Non-sLME Group

Characteristic	sLME (n = 32)		Non-sLME (n = 8)		*P* Value			
	Pre (a)	Post (b)	Pre (c)	Post (d)	a vs b	c vs d	a vs c	b vs d
Grade of pivot-shift test					.890	1.000	1.000	.563
Low grade (grades 0 and 1)	7 (21.9)	27 (84.4)	1 (12.5)	8 (100.0)				
High grade (grades 2 and 3)	25 (78.1)	5 (15.6)	7 (87.5)	0 (0.0)				
KNEELAX arthrometer side-to-side difference, mm	8.44 [7.96, 8.78]	2.42 [2.28, 2.62]	7.06 [6.65, 7.43]	2.30 [2.18, 2.43]	.000*	.014*	.002*	.078 (power: 0.455)
Static ATSLC, mm	6.00 [5.83, 6.23]	6.30 [4.75, 7.08]	6.05 [5.45, 6.80]	1.70 [1.27, 2.28]	.326	.014*	.786	<.001* (power: >0.999)
cLME, mm	1.00 [0.00, 1.92]	1.15 [0.00, 2.20]	0.55 [0.00, 1.33]	0.00 [0.00, 0.00]	.939	.095	.570	.008* (power: >0.999)
sLME, mm	1.65 [1.17, 1.80]	2.70 [2.08, 2.92]	1.55 [1.35, 1.68]	0.00 [0.00, 0.00]	.000*	.014*	1.000	<.001* (power: >0.999)
Lysholm score	59.50 [53.00, 69.75]	90.00 [89.00, 92.00]	61.00 [55.00, 66.00]	92.00 [90.50, 92.25]	.000*	.008*	.866	.298
IKDC score	58.50 [52.00, 61.25]	85.50 [82.75, 89.00]	50.00 [48.75, 52.25]	90.50 [87.50, 92.00]	.000*	.014*	.007*	.053 (power: 0.407)
Healing of lateral meniscus	NA		NA		NA	NA	NA	.566
Completely healed	NA	28 (87.5)	NA	8 (100.0)	NA	NA	NA	
Not completely healed	NA	4 (12.5)	NA	0 (0.0)	NA	NA	NA	

NOTE. Values are presented as median [quartile] or number (%) unless otherwise indicated.

ATSLC, anterior tibial subluxation of the lateral compartment; cLME, lateral meniscal extrusion; IKDC, International Knee Documentation Committee; NA, not applicable; sLME, sagittal lateral meniscal extrusion.

*Statistically significant ($P < .05$).

Preoperative and Postoperative Comparisons Within Each Group

The results of preoperative and postoperative comparisons within each group (Table 4) showed that all the patients had a significant improvement in the Lysholm (59.5 vs 90.0, $P = .000$; 61.0 vs 92.0, $P = .008$, respectively) and IKDC (58.5 vs 85.5, $P = .000$; 50.0 vs 90.5, $P = .014$, respectively) scores, with a significant decrease in KNEELAX SSD postoperatively (8.44 vs 2.42, $P = .000$; 7.06 vs 2.30, $P = .014$, respectively). Meanwhile, in the non-sLME group, the ATSLC and sLME were found to decrease significantly (6.05 vs 1.70, $P = .014$; 1.55 vs 0.00, $P = .014$, respectively) while the cLME also decreased but of no significance (0.55 vs 0.00, $P = .095$). However, in the sLME group, the postoperative ATSLC did not improve compared to the preoperative one (6.00 vs 6.30, $P = .326$). The result of cLME also showed no improvement at final follow-up time, and the postoperative sLME even increased significantly compared with the preoperative one (1.00 vs 1.15, $P = .939$; 1.65 vs 2.70, $P = .000$, respectively).

Preoperative and Postoperative Comparisons Between the 2 Groups

The results of preoperative comparisons between the 2 groups (Table 4) showed significant differences with regard to the IKDC score and SSD (58.5 vs 50.0, $P = .007$; 8.44 vs 7.06, $P = .002$, respectively), while the postoperative results were of no significant difference (85.5 vs 90.5, $P = .053$; 2.42 vs 2.30, $P = .078$, respectively). However, the postoperative results of ATSLC, sLME, and cLME were significantly larger in the sLME group than in the non-sLME group (6.30 vs 1.70, $P < .001$; 2.70 vs 0.00, $P < .001$; 1.15 vs 0.00, $P = .008$, respectively).

Discussion

For all 40 patients in this study, the postoperative parameters, including grade of pivot shift, SSD, ATSLC, Lysholm score, and IKDC score, were significantly improved compared with the preoperative ones. In addition, no significant change was observed regarding cLME. However, postoperative sLME was detected to be significantly larger than the preoperative one. Further comparisons, where patients were divided into 2 subgroups according to the occurrence of sLME, showed significant differences in PTS, ATSLC, and cLME.

As previously described,[6,7,11] the clinical outcomes with regard to cLME on MRI postoperatively were significantly improved after the repair procedure for PLMRTs. Our results also demonstrated a decreased cLME, although no significant difference was detected because of the relatively small preoperative data. Further, all 40 patients underwent second-look arthroscopy (Fig 3), and the second-look results of 32 patients with sLME showed an unhealed meniscal root

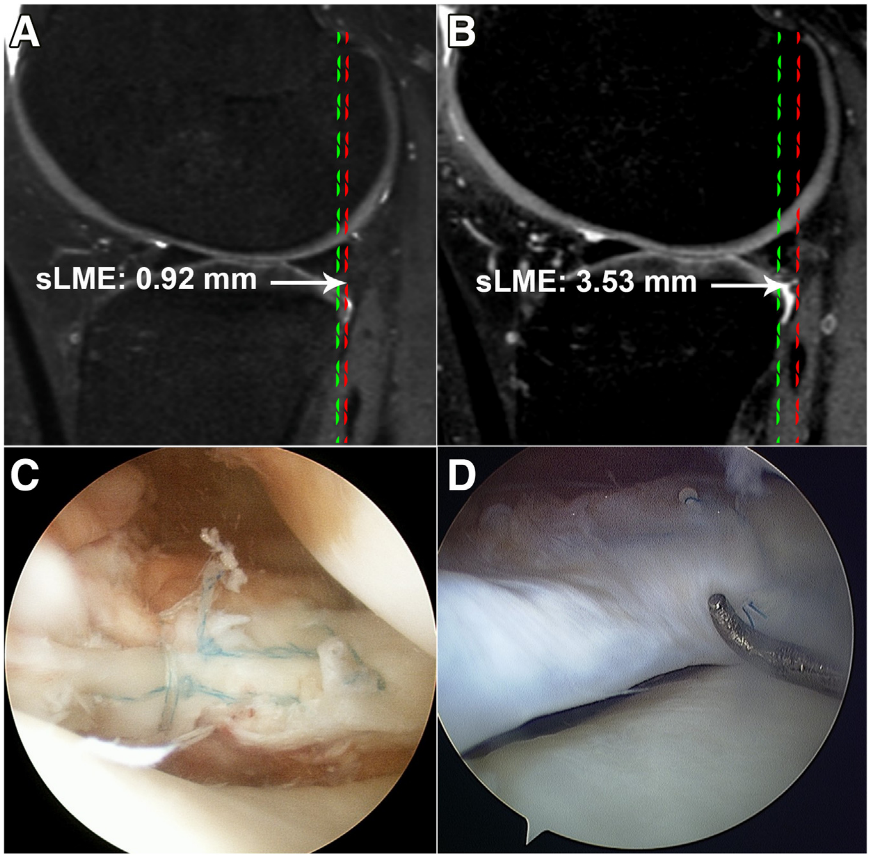

Fig 3. Representative magnetic resonance and arthroscopic images of the sagittal lateral meniscal extrusion (sLME) and lateral meniscal injury and healing patterns. (A, B) The values of pre- and postoperative sLME were 0.92 mm and 3.53 mm, respectively. (C) Arthroscopic findings. H-plasty side-to-side repair technique for arthroscopic repair of type II posterior lateral meniscus root tears. (D) Second-look arthroscopy shows complete healing at the site of the radial tear at 15.5 months postoperatively.

in 1 patient and partial healing of the meniscal root in 3 patients. The total healing rate of 40 patients (complete or partial healing) was 97.5%, which was a satisfying result, although a number of patients (32 of 40) reported an increased sLME, which indicated a lax meniscus with scar healing after repair. In the area of the meniscal root, the tissue was subjected to more stress because of the transduction of force from the meniscal body to the insertions. We hypothesize that the constant stress led to a loose construction of circumferential fibers after repair of PLMRTs, and the externalized representation was a meniscal extrusion on MRI.

The static ATS was reported by Almekinders et al.[20-22] in consecutive studies, where some patients after a failed ACLR had a significantly larger and fixed anterior tibial subluxation on x-ray radiographs. The authors concluded that the subluxation was due to the malalignment of the tibia to the femur during ACLR surgery. With the contracture of the posterior cruciate ligament and the formation of scar tissue in the femoral condyle, the tibia was fixed at an anterior position relative to the femur, which could not be reduced by a posterior direction force. They also mentioned that from the x-ray images of those patients with unsuccessful ACLR, an impression of notch impingement could be left to surgeons, but since the tibial tunnel placement was satisfactory, this might be was evidence of fixed and irreducible anterior tibial subluxation. Further, Tanaka et al.[23] put forward a measurement to accurately quantify the abnormal tibiofemoral relationship in ACL-deficient patients via MRI. Their results showed a significantly increased ATS in patients with unsuccessful ACLR (3.9 mm on average) compared to that in those with acute ACL injury (0.8 mm on average). Their results also suggested that a rotational laxity, an internal rotation of the tibia in full extension, could partially explain the ATS in ACL-deficient knees. With in-depth research on the relationship between ATS and ACL injury, the skeletal factors have raised increasing attention. Song et al.[31] found that an increased PTS (≥10°) was an independent anatomic risk factor of increased ATS of the lateral compartment (≥6 mm) in acute noncontact ACL injuries. PTS has thus been verified to be closely related to ACL injuries or failed ACLR by influencing the biomechanics, including increasing tibial shear force, ACL loading, static ATS, and so on. In particular, when a patient with an ACL injury has a higher degree of PTS, the anatomic structure may apply more stress on the meniscal root,[34,35] which is a secondary knee stabilizer, but with the presence of injuries on the meniscal root, damage of the

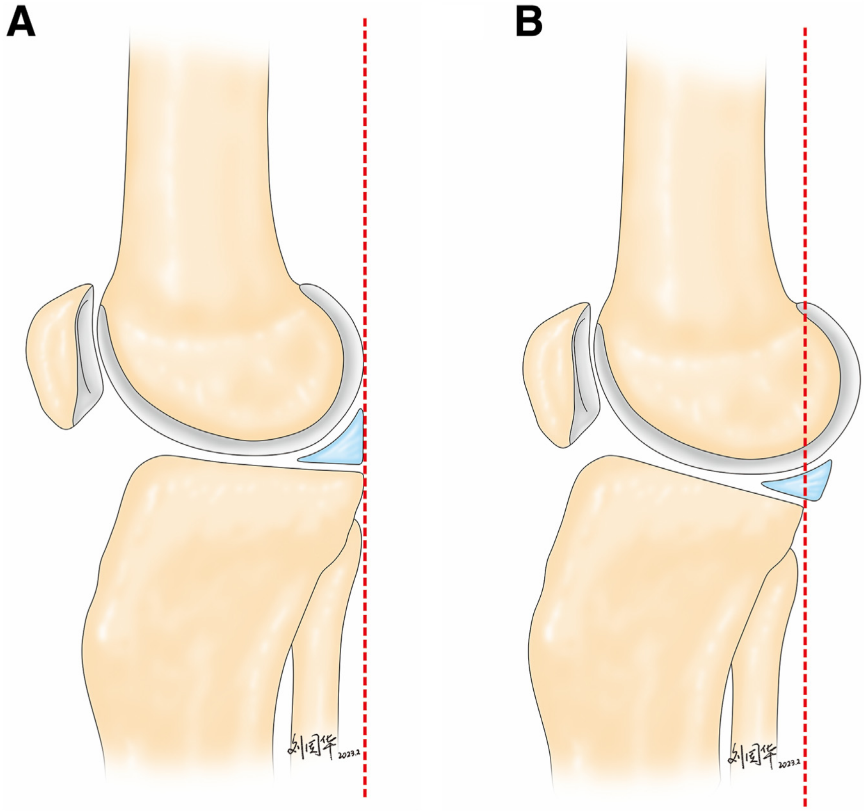

Fig 4. Schematic diagram showing the relationship between ATSLC, PTS, and sLME. (A) A knee joint with normal tibiofemoral relationship and PTS usually does not present sLME. (B) With the development of ATSLC and an increased PTS, the posterior lateral meniscus root may present a posterior displacement, that is, manifested as an sLME. (ATSLC, anterior tibial subluxation of the lateral compartment; PTS, posterior tibial slope; sLME, sagittal lateral meniscal extrusion.)

integrity of the meniscus could not maintain the “wedge effect” exerted by the meniscal root.[25] McDonald et al.[24] concluded a similar result that medial and lateral meniscal tears were an independent predictor of increased ATS (≥6 mm) of the lateral compartment, demonstrating an important role the secondary stabilizer could play in maintaining knee stability after ACL injuries.

In this study, we found that 8 patients had a decreased sLME postoperatively (1.55 vs 0.00 mm), while the others (n = 32) had an increased one (1.65 vs 2.70 mm). Among the patients who had an increased sLME, the postoperative ATSLC was increased compared with the preoperative one (6.00 vs 6.30 mm), as well as the cLME (1.00 vs 1.15 mm). On the contrary, patients without sLME also had a decreased ATSLC and cLME postoperatively (6.05 vs 1.70 mm and 0.55 vs 0.00 mm, respectively). In addition, the median PTS in all patients was more than 10°. Further, when a comparison was performed between patients with or without sLME, there was a significant difference in the degree of PTS (11.80° vs 10.20°). Combining the above results, a reasonable explanation is that a larger PTS may lead to an increased tension in the reconstructed ACL and thus an increased stress on the secondary stabilizers, especially the posterior lateral meniscus root (PLMR), which may gradually present extrusion on both sagittal and coronal planes on MRI (Fig 4).[19] Additionally, since PTS was reported as a risk factor of residual ATSLC after ACLR,[36] the PLMR could be relatively posterior to the tibia, attributed to the traction of the meniscofemoral ligament, which anchors at the PLMR and the femur.[11] The posterior displacement of the PLMR thus could be extended with the development of ATSLC. Besides, the H-plasty suture repair that anchors the meniscal root to the meniscofemoral ligament could have a fixed effect, which might be also involved in the extrusion of the lateral meniscus.

There have been limited studies focusing on LME, especially sLME. Gentili et al.[29] found that in the sagittal position on MRI, a posterior displacement of the lateral meniscus of more than 3.05 mm was considered significantly different between ACL tear and normal ACL patients. In addition, the sensitivity and specificity were 44% and 94%, respectively, when the displacement was more than 3.5 mm, and 20% and 100%, respectively, when the displacement was more than 5 mm.[29] Wenger et al.[37] reported a significantly greater proportion of patients who had pain with a mean extrusion ≥3 mm in either the medial or the lateral compartment in a coronal view on MRI. Furumatsu et al.[38] reported that the mean medial meniscal extrusion in a coronal view on MRI was 3 mm when patients had symptoms of posteromedial pain and were diagnosed with posterior medial meniscus root tears within 1 month, and the extrusion could rapidly progress to a mean of 5.8 mm within 1 year. It should be noted that although previous studies chose a meniscal extrusion of more than 3 mm as a boundary to consider abnormality,[29,39,40] no standard threshold of LME on MRI has been determined, neither sagittal nor coronal, because of the variations between medial and lateral menisci regarding anatomic factors and ability of motion. In addition, there is also limited evidence showing how much distance of an extrusion would bring about clinical symptoms. Based on those factors, we grouped patients by whether sLME was presented postoperatively to detect the differences in clinical outcomes. Although the postoperative results of the pivot-shift test, side-to-side difference, and subjective assessment scores showed no significant difference between the 2 groups, patients with sLME had significantly larger ATSLC and cLME than patients without sLME at the final follow-up time. Considering the relatively short follow-up time of this study (24 months at least), the alterations of radiographic manifestations might negatively affect the knee joint functions and cartilage states in the long run.

The most direct impact of meniscal extrusion is the loss of the wedge effect,[41] which mainly depends on the posterior horn or root of the meniscus. In the lateral compartment, the posterior meniscal structure critically influenced the rotational stability of the knee joint.[15-18] The postoperative outcomes showed that most patients had improvement in pivot-shift examination, while a small portion of patients with sLME still showed a high-grade pivot shift (Table 3). Therefore, it was reasonable to conclude that preoperatively, a high-grade pivot shift is a mixed result of ACL injuries, meniscal root tears, and other soft tissue injuries, and postoperatively, a high-grade pivot shift is a consequence of the attenuated wedge effect of the meniscal root caused by sLME and steeper PTS, whose synergistic effects decreased the height, width, and area of the meniscal root on the tibial plateau.[34,35] Based on the follow-up results of this study, it is possible that postoperative high-grade pivot might be related to the anterolateral ligament (ALL) injuries but not significantly associated with failed ACL graft because the lack of significant difference in postoperative KNEELAX SSD suggests that there is no significant disparity in anterior stability of the knee joint between the sLME and non-sLME groups. Hence, these 2 groups might only differ in terms of rotational stability, while the relationship between high-grade pivot and unhealed meniscus and ALL injuries remains.

Considering the clinical relevance, when dealing with patients with complete ACL rupture and concomitant type II PLMRTs, it is of importance to evaluate their bony morphology carefully. ACL should be reconstructed with caution, and a suitable technique should be adopted to repair the meniscus when a patient presents a large PTS (≥10°). Second, during ACLR surgery, attention should be paid to restoring the correct position of the tibia relative to the femur, thus avoiding tibiofemoral displacement postoperatively. Last but not least, if there are factors that affect the postoperative ATSLC meniscal healing (such as large PTS, high grade of pivot shift, and poor quality of meniscus stump that is not suitable for side-to-side suture repair), additional procedures such as transtibial pull-out meniscal suture repair, lateral extra-articular tenodesis, or tibial osteotomy should be taken into consideration.

Limitations

There are some limitations in the present study. First, the PTS was measured using x-ray radiographs, which were less accurate than the MRI scans. Second, 23 of 40 (80%) patients had a high-grade pivot shift before surgery, but 5 of 40 (12.5%) patients still showed a postoperative high-grade pivot shift. In addition, preoperative static ATSLC did not improve after surgery in the sLME group, and the potential ALL injury should be considered a risk factor for postoperative high-grade pivot shift and postoperative static ATSLC. Third, the effect of noncompletely healed lateral meniscus and postoperative high-grade pivot shift was not investigated for possible risk factors for sLME. Fourth, because of the retrospective study design, incomplete data might lead to information bias, and the quality and reliability of retrospective studies are limited by the availability of data. In addition, constrained by the limited sample size, this study may have been underpowered to detect statistical differences in certain indicators.

Conclusions

Clinical outcomes after type II PLMRT repair with primary ACLR were significantly improved, except for LME, at the 2-year postoperative follow-up. After repair of type II PLMRT injuries, the presence of sagittal LME was associated with increased PTS and ATSLC.

Disclosure

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