One-Stage Anatomical Revision Anterior Cruciate Ligament Reconstruction: Results According to Tunnel Overlaps

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Purpose: To present clinical results according to tunnel overlap in 1-stage anatomical revision anterior cruciate ligament reconstruction (ACLR). **Methods:** All patients who underwent revision ACLR performed by a single surgeon (J.H.A.) from 2012 to 2017 and were followed up for >24 months were retrospectively evaluated. The exclusion criteria were concomitant ligament injury, including medial collateral ligament injury, modified Outerbridge grade $\geq$3 cartilage lesion, and severe meniscus defects. Tunnel overlap was measured on 3-dimensionally reconstructed computed tomography images. Patients in the nonoverlapped femoral tunnel group (group NO, n = 52) were treated with new tunnel drilling that completely avoided previous tunnels, and those in the overlapped femoral tunnel group (group O, n = 41) were treated with a new tunnel that overlapped with previous tunnels. Clinical outcomes were evaluated using the subjective International Knee Documentation Committee (IKDC) and Lysholm scores. Knee joint stability was measured using the Lachman and pivot shift tests. Patients with femoral tunnel widening of $\geq$14 mm underwent 2-stage ACLR. **Results:** The mean follow-up duration of 93 patients was 46.9 months (range, 24-97 months). All preoperative subjective and objective IKDC ($P<0.001$) and Telos stress test scores ($P = .016$) were significantly improved at the last follow-up. Forty-one patients had overlapping femoral tunnels, whereas 87 had overlapping tibial tunnels. At the last follow-up, subjective IKDC and Lysholm scores (73.6 ± 15.3 vs 74.9 ± 12.1, $P = .799$ and 80.0 ± 19.2 vs 81.44 ± 13.5, $P = .505$, respectively) and objective pivot shift (IKDC grade) in the Lachman test ($P = .183$ and $P = .450$, respectively) did not differ significantly between groups NO and O, respectively. **Conclusions:** One-stage anatomical revision ACLR significantly improved the clinical results. Most tibial tunnels (94%) and approximately one-half (44%) of the femoral tunnels overlapped. The overlapped femoral tunnel group did not show inferior outcomes or stability. **Level of Evidence:** Level III, cohort study.

See commentary on page 1233

The goal of revision anterior cruciate ligament reconstruction (ACLR), similar to that of primary ACLR, is to provide a stable anterior cruciate ligament (ACL) with kinematics similar to those of the native anatomical knee.[1] Various factors such as tunnel position, tunnel enlargement, bone graft, graft type, and fixation devices are considered in choosing the surgical strategy for revision ACLR.[2-4]

The reconstruction tunnel position and size are important factors for 1- and 2-stage revision ACLRs.[5-7] One-stage revision ACLR can be performed with or without simultaneous tunnel augmentation if the previous femoral and tibial tunnels are correctly positioned with or without tunnel widening or osteolysis. One-stage revision ACLR has the advantage of rapid recovery, fewer operative procedures, and knee stability restoration without an ACL-deficient interval.[8] In contrast, 2-stage reconstruction is considered when the previous tunnel shows significant widening or the apertures of the previous tunnels interfere with those of the new tunnels.[9] Two-stage revision ACLR typically

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includes an initial bone graft procedure to fill the widened or malpositioned tunnels and requires adequate time postoperatively to ensure graft incorporation.[9,10]

During revision ACLR, restoration of the femoral tunnel to its anatomical position is crucial. Over the past 2 decades, the graft position in ACLR has shifted from an isometric point to an anatomical position.[11,12] Therefore, 1-stage revision ACLR can be performed by drilling new femoral tunnels that bypass the existing ones. When a previous bone tunnel is not in the anatomical position, the planned new tunnel can be placed in the anatomical position without overlapping. However, revision ACLR can require 2-stage surgery because of significant tunnel widening and complicated overlapping between the pre-existing and planned femoral tunnels.[5,13]

To date, studies on 1-stage revision ACLR surgery have usually focused on graft materials and tunnel widening.[1,3,14,15] Limited studies have investigated tunnel overlapping, a common concern during 1-stage revision ACLR. Therefore, this study aimed to present clinical results according to tunnel overlaps in 1-stage anatomical revision ACLR. We hypothesized that the results of 1-stage revision ACLR using soft-tissue allografts would differ between patients with overlapping and nonoverlapping femoral tunnels.

Methods

Patients

Revision ACLR was performed from July 2012 to April 2017 by a single experienced surgeon (J.H.A.). The surgical indications for revision ACLR included persistent or recurrent subjective instability after the primary ACLR, limited daily or athletic activities, objective instability with both positive Lachman and pivot shift test results, and magnetic resonance imaging demonstrating previous ACL graft failure. The inclusion criteria were as follows: (1) retear after primary ACLR; (2) 1-stage revision ACLR using the outside-in technique; (3) a minimum follow-up of 24 months; and (4) age <55 years. The exclusion criteria were as follows: (1) concomitant ligament injury, including the medial collateral ligament; (2) modified Outerbridge grade >2 cartilage damage; and (3) severe meniscal defects such as a subtotal or total meniscectomy state. Patients with severe femoral tunnel widening (>14 mm) and anatomical femoral tunnel placement requiring bone grafting and a 2-stage operation were also excluded to minimize heterogeneity between the patient groups. Patients who met the selection criteria were divided into the nonoverlapping (group NO) and overlapping femoral tunnel groups (group O; Fig 1).

The following options for femoral tunneling in revision ACLR were available: (1) drilling new tunnels that avoid existing tunnels, (2) re-reaming existing tunnels, (3) drilling divergent tunnels, and (4) bone grafting and staged revision reconstruction. Patients who required the drilling of new tunnels to avoid existing tunnels were further divided into groups: new tunnels were either drilled to completely (group NO) or incompletely (group O) avoid pre-existing tunnels. Group O included the following approaches: new tunnels were drilled to incompletely avoid existing tunnels (group O1),

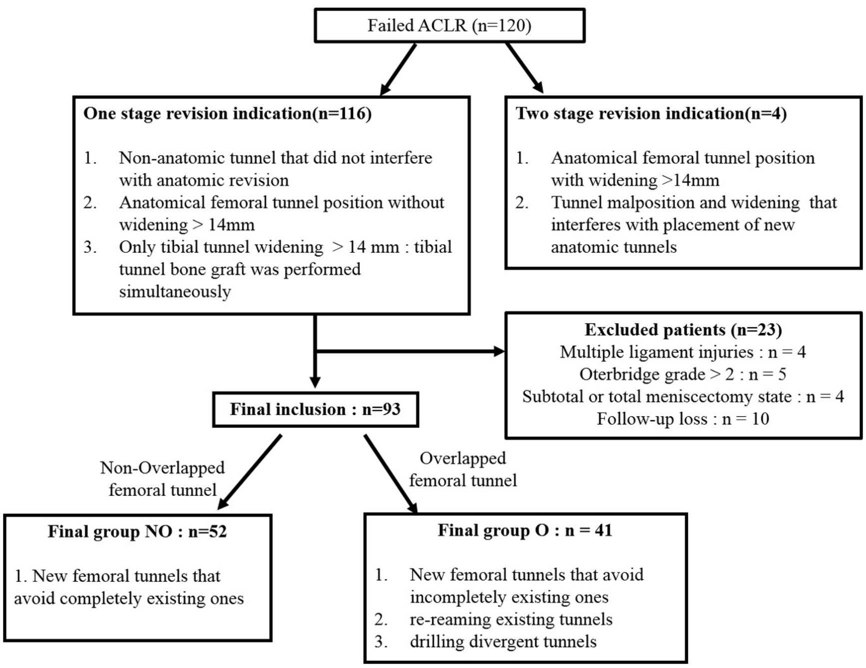

Fig 1. Flowchart showing the patient selection process (ACLR, anterior cruciate ligament reconstruction; NO, non-overlapped femoral tunnel; O, overlapped femoral tunnel.)

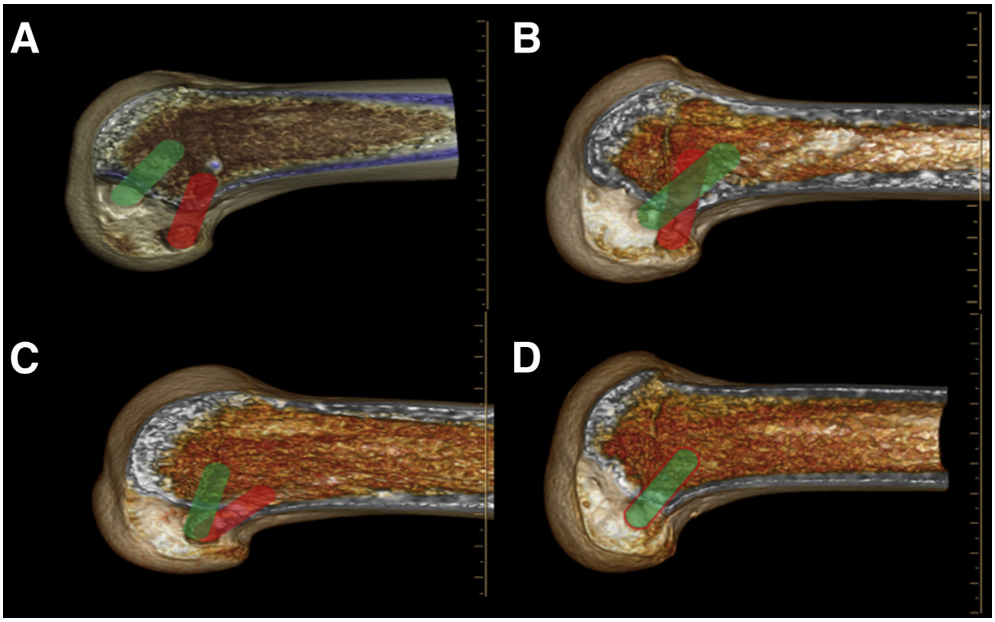

Fig 2. The positions of the previous and new femoral tunnels are evaluated on 3-dimensional—reconstructed images. Green cylinder, previous tunnel. Red cylinder, new tunnel. Groups (A) NO, (B) O1, (C) O2, and (D) O3.

divergent tunnels were drilled (group O2), and existing tunnels were re-aimed (group O3; Fig 2). Preoperative demographic variables did not differ significantly between groups NO and O (Table 1).

Surgical Techniques and Rehabilitation

First, primary ACL graft failure was confirmed on arthroscopic examination, and 1-stage revision ACLR was performed by the same surgeon (J.H.A.) using a

Table 1. Patients' Preoperative Demographic Data and Clinical Characteristics

Characteristic	Overall	Group NO (n = 52)	Group O (n = 41)	*P* Value*
Age, y	32.63 ± 8.42	34.0 ± 8.4	31.0 ± 8.3	.083
Sex				.178
Male/female	76/17	40/12	36/5	
Follow-up duration, mo	46.9 ± 21.4	45.2 ± 20.3	49.4 ± 23.2	.341
Time from primary ACLR to failure, y	7.6 ± 5.6	9.1 ± 5.9	5.8 ± 4.7	.04
Time from failure to revision, mo	21.0 ± 38.0	21.8 ± 34.8	19.9 ± 42.1	.817
Cause of graft failure				.671
Trauma history	56	30	26	
No trauma history	37	22	15	
Body mass index	25.48 ± 3.18	25.4 ± 3.0	25.6 ± 3.4	.750
Tibial posterior slope	12.2 ± 3.78	11.7 ± 3.6	12.9 ± 3.9	.127
Intercondylar notch width index	24.39 ± 4.39	24.2 ± 5.05	24.6 ± 3.4	.651
Pivot shift (preoperative), n, 0/1/2/3	0/25/47/21	0/17/23/12	0/8/24/9	.298
Lysholm score	59.76 ± 17.91	61.3 ± 15.2	57.7 ± 20.9	.356
Subjective IKDC score	53.84 ± 15.16	55.2 ± 15.0	52.2 ± 15.3	.363
Preoperative Tegner score	5.2 ± 1.1	5.1 ± 1.2	5.3 ± 1.1	.594
Side-to-side difference on the Telos device, mm	9.82 ± 3.34	9.85 ± 3.33	9.78 ± 3.4	.926
IKDC grade in the Lachman test, n, A/B/C/D	0/10/59/24	0/6/35/11	0/4/24/13	.744
Type of graft, n (%)				1.00
Autograft	8 (9%)	5 (10%)	3 (7%)	
Allograft	85 (91%)	47 (90%)	38 (93%)	
Meniscus surgery, n (%)				.499
None	35 (37.6%)	20 (38.5%)	15 (36.6%)	
Meniscal repair, medial or lateral	36 (38.7%)	22 (42.3%)	14 (34.1%)	
Partial meniscectomy, medial or lateral	22 (23.7%)	10 (19.2%)	12 (29.3%)	

NOTE. Data are presented as means ± standard deviations unless otherwise indicated.

ACLR, anterior cruciate ligament reconstruction; IKDC, International Knee Documentation Committee; NO, nonoverlapped femoral tunnel; O, overlapped femoral tunnel.

*Independent *t*-test or χ^2 test was used to compare groups NO and O.

single-bundle graft. A tibialis anterior tendon or Achilles tendon allograft was used routinely for 1-stage revision ACLR unless a patient had an intact harvestable hamstring tendon, in which case a 4-strand hamstring tendon autograft was used. The allograft (fresh frozen) was irradiated with 12.8 to 19.8 kGy and controlled by a tissue-preservation technique (Allowash Process; LifeNet Health, Virginia Beach, VA). Graft selection was individualized by factors such as size and position of tunnel widening and previous surgery. We prefer using a single-loop tibialis allograft for revision ACLR, with a 9-mm allograft composite. A single-bundle Achilles allograft was used in case of tibial tunnel widening owing to the additional bone graft with remnant bone. We also used a double-loop semitendinosus and gracilis autograft in cases involving previously unharvested ipsilateral semitendinosus and gracilis autografts. Of the 93 patients, 77 (82.8%) had tibialis anterior tendon allografts, whereas 8 (8.6%) had Achilles allografts. In 8 knees (8.6%), revision reconstruction was performed with double-loop semitendinosus and gracilis autografts.

Indications for 1-stage revision ACLR included a previous anatomical tunnel positioned on both the femoral and tibial ACL footprints, a previous bone tunnel diameter <14 mm, or a pre-existing tunnel sufficiently malpositioned to avoid interference with the anatomical placement of a new tunnel. If the tibial tunnel diameter was widened to >14 mm, 1-stage revision ACLR was performed after allograft bone chips or autograft bone blocks were packed into the tibial tunnels. If the previous femoral tunnel was widened to >14 mm and placed at the anatomical tunnel position, 2-stage revision ACLR was indicated. If the previous femoral tunnel width was >14 mm and the tunnel was placed in a nonanatomical area without interference with a new tunnel, 1-stage revision ACLR was indicated.

To observe the posterior aspect of the lateral femoral condyle, an arthroscope was inserted through the anteromedial portal and reached the posterolateral (PL) compartment through the interval between the ACL and the lateral femoral condyle. A 70° arthroscope was then inserted through the PL portal and advanced to reach the posterior aspect of the intercondylar notch. The posterior portion of the previous ACL graft or previous tunnel could be observed using this approach. The failed graft and fibrous soft tissue were minimally debrided using a shaver or electrocautery. We preserved the synovialized remnant graft as much as possible. The previous remnant ACL graft and inner margin of the cartilage were visualized through the posterolateral viewing portal (Fig 3: PL viewing portal arthroscope). Posterior viewing portals provide a good view of the direct insertion of the femoral footprint and have the advantage of remnant preservation in native ACL footprint observation. Under visualization through the PL portal, the FlipCutter guide tip (Arthrex, Naples, FL) was positioned at the center of a previous tunnel if the previous femoral tunnel was located at the anatomical position. However, when the previous tunnel was not located at the anatomical position, as assessed using preoperative computed tomography (CT), an entirely new femoral tunnel was drilled. The

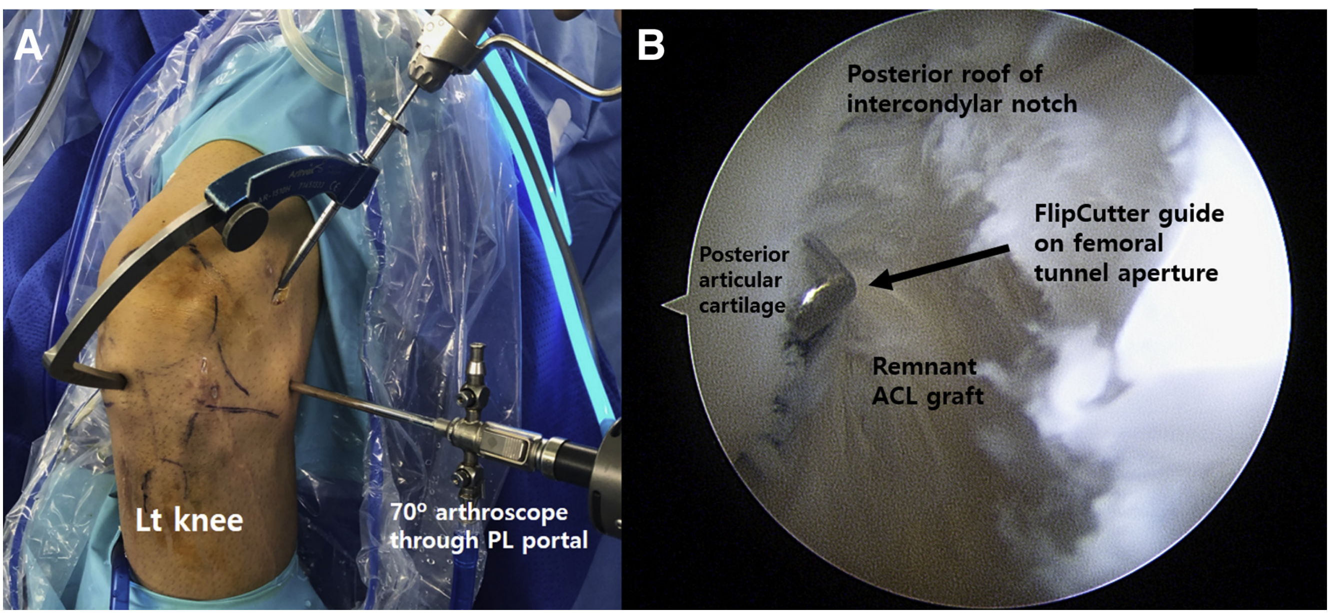

Fig 3. Outside-in photograph of the formation of a femoral tunnel under visualization through the PL portal in the right (left) knee (A). The arthroscope is inserted through the PL portal, while the guide was introduced through the anterolateral portal (B). (ACL, anterior cruciate ligament; Lt, left; PL, posterolateral.)

guide tip was placed 4 to 5 mm anterodistal to the posteroproximal margin of the ACL femoral footprint. The center point of the anteromedial tunnel usually shows good correspondence with the anteroproximal end of the cartilage margin.[16] After the guide pin was drilled into the intra-articular cartilage using the outside-in technique, the FlipCutter was engaged into the joint and retrodrilled for approximately 25 to 30 mm to generate a femoral tunnel. When a tibial tunnel was present in a satisfactory position preoperatively, it was reused. A small tunnel was first generated and then dilated to 9 mm using a dilator (CONMED Linvatec, Utica, NY) to prevent a large bone defect and preserve the previous ACL graft.

Staged operations were performed in 4 knees because of a dilated femoral tunnel, whereas reconstruction with a 1-stage bone graft at a wide tibial tunnel with residual Achilles bone, allo-bone chips, or an autologous iliac bone graft was performed in 13 knees. The Achilles tendon allograft was passed through the tibial tunnel and biointerference screw (BioScrew; CONMED Linvatec). An additional screw (4.0-mm cancellous screw; DePuy Synthes, Warsaw, IN) and washer were used for tibial and femoral fixations. Unless tunnel widening was present, the tibialis anterior allograft and hamstring autograft were passed through the tibial tunnel, and the ACL tightRoupe (Arthrex) was used for femoral fixation. A biointerference screw (BioScrew), an additional screw (4.0-mm cancellous screw), and a washer were used for tibial fixation.

The same postoperative rehabilitation regimen was used for all patients, except for those who required meniscal repair. All patients began immediate isometric quadriceps and active range-of-motion exercises. During the first postoperative week, partial weight-bearing within the tolerable range was allowed, an ACL brace was fitted, and range-of-motion exercises were performed with a 15° increase each week. At 4 and 6 weeks postoperatively, 90° and 135° motions were allowed, respectively. At 6 and 9 months postoperatively, straight-line running and direction changes while running were allowed, respectively. When meniscal repair was performed, rehabilitation was modified to exclude weight-bearing activities and 90° knee flexion for the first 6 weeks.

Tunnel Overlap Measurement

Tunnel overlap was measured on 3-dimensional (3D)-reconstructed CT images. Femoral tunnel diameter and overlap were evaluated at the medial wall of the lateral femoral condyle, and tibial tunnel diameter and overlap were evaluated in the tibial plateau view using 3D CT. Tunnel overlap was determined by measuring the size of the previous and new femoral tunnel apertures and overlapping areas. We drew a maximum circle with the previous and new apertures as its center and measured the overall and overlapped diameters (Fig 4). If the overlapped diameter exceeded 50% of the overall diameter, we considered drilling divergent tunnels (group O2) or re-reaming existing tunnels (group O3). If the overlapped diameter did not exceed 50% of the overall diameter, we considered drilling new tunnels to incompletely avoid existing tunnels (group O1). Two orthopaedic surgeons (D.W.S. and D.W.P.) retrospectively reviewed the CT images and reached a consensus on femoral tunnel overlap. In cases of disagreement, a third author resolved the dispute. The mean dosage of radiation exposure on the preoperative and postoperative knee CT scans of 10 patients was 0.18 ± 0.14 mSv. The study protocol was approved by our institutional review board.

Assessment of Clinical Outcomes

Clinical evaluations and physical examinations were usually performed preoperatively, 6 months postoperatively, and annually thereafter by one senior surgeon (J.H.A.). The Lysholm, subjective International Knee Documentation Committee (IKDC), and Tegner

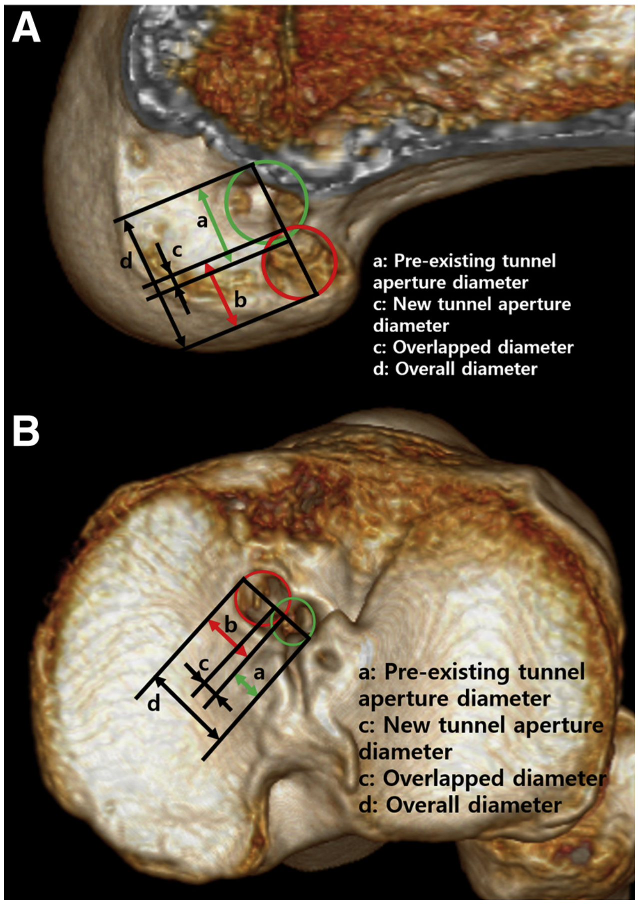

Fig 4. (A) Measurement of femoral tunnel overlap using a 3-dimensionally–reconstructed computed tomography image. (B) Measurement of tibial tunnel overlap using the plateau view on computed tomography.

Table 2. Overlapping of Femoral and Tibial Tunnels

	Tibial Tunnel	Femoral Tunnel
Overlapped tunnel		
Drilling a new tunnel that incompletely avoids the existing tunnel	7	23
Drilling a divergent tunnel	11	11
Re-reaming an existing tunnel	69	7
Nonoverlapped tunnel		
Drilling a new tunnel that completely avoids the existing tunnel	6	52

activity scale scores were used in the subjective knee function evaluations. For objective assessment, the Lachmann, pivot short, and anterior laxity tests were used. Anterior laxity was evaluated using a side-to-side difference on stress radiography using the Telos device (Telos, Weiterstadt, Germany) with the knee in 30° flexion and 15 N anterior stress. The minimal clinically important difference (MCID) and minimal detectable change (MDC) were calculated in accordance with the guidelines of Harris et al.[17] The MCID for the IKDC score was 16.7, whereas the MDC for the Lysholm score was 8.9.

Tunnel Placement Assessment

The quadrant method, described by Forsythe et al.,[18] was used to measure the location of the previous and new femoral tunnels (Fig 4A). Femoral tunnel position was evaluated on the medial side of the lateral femoral condyle on 3D CT. A rectangular measurement frame was drawn over the mediolateral view of the lateral condyle by placing the superior border at the intercondylar notch roof (*x*-axis). The *y*-axis was perpendicular to the *x*-axis in the high-low direction in the plane of the condyle wall. The positions of the previous and new tunnels were determined as the percentage of the length of the superior border at the intercondylar notch roof (*x*-axis) and the line perpendicular to the *x*-axis (*y*-axis) and were compared using the quadrant method (Fig 4A). The tibial tunnel position was calculated as the percentage of the length of the tibial plateau in the anteroposterior and medial-lateral directions (Fig 4B). Scans were independently evaluated by 2 orthopaedic surgeons (D.W.S. and D.W.P.). Each patient underwent 3D CT 2 days after surgery. The measurements acquired by the 2 surgeons were averaged.

Graft Failure

Graft failure was defined as the need for re-revision surgery after 1-stage revision ACLR. If a patient's clinical history and physical examination findings were compatible with re-rupture of the ACL, ACL graft failure was confirmed using magnetic resonance imaging. The number of graft failures was compared between groups NO and O.

Statistical Analyses

All statistical analyses were performed using SPSS, version 22.0 (IBM Corp., Armonk, NY). A *Z* test was used to compare clinical outcomes and stability between groups NO and O. To detect a difference of 10 points in the subjective IKDC score between the 2 groups, with an alpha of 0.05 and 80% power, the required sample size was 36 patients per group. This study included at least 41 patients per group. The reliability of the measurement of femoral tunnel overlap on 3D CT was assessed by calculating the intraclass correlation coefficient, which quantifies the proportion of differences due to measurement variability. The interobserver and intraobserver reliabilities were 0.821-0.952 and 0.832-0.948, respectively, indicating good reliability of the measurements of femoral tunnel overlap on CT. Parametric and nonparametric variables were compared between the groups using an independent *t* test or the Mann−Whitney *U* test. A paired *t* test or the Wilcoxon signed-rank test was used to compare preoperative and postoperative parametric or nonparametric variables between the groups. The χ^2 or

Table 3. Subjective and Objective Outcomes at the Last Follow-Up

	Overall	Group NO (n = 52)	Group O (n = 41)	*P* Value*
Subjective outcome measure				
Subjective IKDC score	74.1 ± 14.0	73.6 ± 15.3	74.9 ± 12.1	.799
Lysholm score	80.6 ± 17.0	80.0 ± 19.2	81.44 ± 13.5	.505
Tegner score	6.3 ± 1.0	6.4 ± 1.0	6.2 ± 1.1	.354
Objective outcome measure				
IKDC grade in the Lachman test, A/B/C/D	69/18/3/3	42/6/3/1	27/11/1/2	.304
Pivot shift, n, 0/1/2/3	67/18/6/1	40/8/4/0	28/10/2/1	.433

Data are presented as means ± standard deviations unless otherwise indicated.

IKDC, International Knee Documentation Committee; NO, nonoverlapped femoral tunnel; O, overlapped femoral tunnel.

*An independent *t* test or χ^2 test was used to compare groups NO and O.

Fisher exact test was used to compare categorical data. For the χ^2 test for trends, a linear-by-linear association was assessed. Statistical significance was set at $P < .05$.

Results

Demographics

Of the 116 patients enrolled, 23 were excluded because of multiple ligament injury, Outerbridge grade ≥2 cartilage damage, a subtotal or total meniscectomy state, or follow-up loss (Fig 1). The mean follow-up durations (months) for groups NO and O were 45.2 (range, 24-83) and 49.4 (range, 24-97), respectively.

Tunnel Overlap

Of 93 patients, 41 (44%) and 83 (89%) had femoral and tibial overlapped tunnels, respectively (Table 2). Group NO consisted of 52 patients; group O comprised 41 patients. Groups O1, O2, and O3 comprised 23, 11, and 7 patients, respectively. The overall and overlapped diameters were 15.5 ± 1.8 and 1.9 ± 1.0 mm in group O1, 9.9 ± 2.0 and 7.9 ± 3.0 mm in group O2, and 9.4 ± 1.8 and 9.4 ± 1.8 mm in group O3, respectively.

Clinical Outcomes

The mean subjective IKDC score improved from 53.8 ± 15.2 preoperatively to 75.7 ± 14.0 postoperatively ($P <$ .001), with 84 of 93 patients achieving the MCID. The mean objective IKDC score also improved ($P < .001$). The mean Lysholm score improved from 51.2 ± 19.0 preoperatively to 80.6 ± 17 postoperatively ($P < .001$), with 83 of 93 patients achieving the MDC. The side-by-side difference on radiographic Telos stress tests improved from 8.6 ± 4.4 mm preoperatively to 2.3 ± 2.7 mm postoperatively ($P = .016$). However, the subjective IKDC, Lysholm, and Tegner scores did not differ significantly between groups NO and O at the last follow-up (Table 3). The preoperative Lachman grade was 2 or 3 in 46 (88.5%) and 37 patients (90.2%) in groups NO and O, respectively ($P = .783$). Postoperatively, 42 (80.7%) and 27 patients (65.9%) in groups NO and O, respectively, showed a negative pivot shift test result ($P = .103$).

Tunnel Position

Using the quadrant method, the average distances from the center of the previous femoral tunnel were 40.1% ± 10.5% and 15.1% ± 6.8% on the *x*- and *y*-axes, respectively. The average distances from the center of the new femoral tunnel were 23.4% ± 5.4% and 24.5% ± 8.0% on the *x*- and *y*-axes, respectively (Fig 5). In group O, the previous tunnel was placed closer to the anatomical position (deeper and lower than in group NO); the new femoral tunnel was positioned at a shallower and higher location than that in in group NO (Fig 6). Between groups NO and O, the mean tibial tunnel position was not significantly different in the anteroposterior direction, as measured from the anterior edge of the tibial plateau. However, the mean tibial tunnel was positioned 1.7 mm more medially in group O than in group NO (Table 4).

Failure Rate

Graft failure requiring re-revision surgery occurred in 4 and 3 patients in groups NO and O, respectively. We found no significant difference in the re-rupture rate ($P = .651$). Graft failure occurred only in cases of revision ACLR using an allograft. We could not compare the allograft and autograft results because the number of autograft results was small. Among the patients in group O, 2 and 1 patients were included in groups O1 and O2, respectively. None of the patients showed re-tearing in group O3. Seven patients had Lachman and pivot shift test scores ≥2. They did not

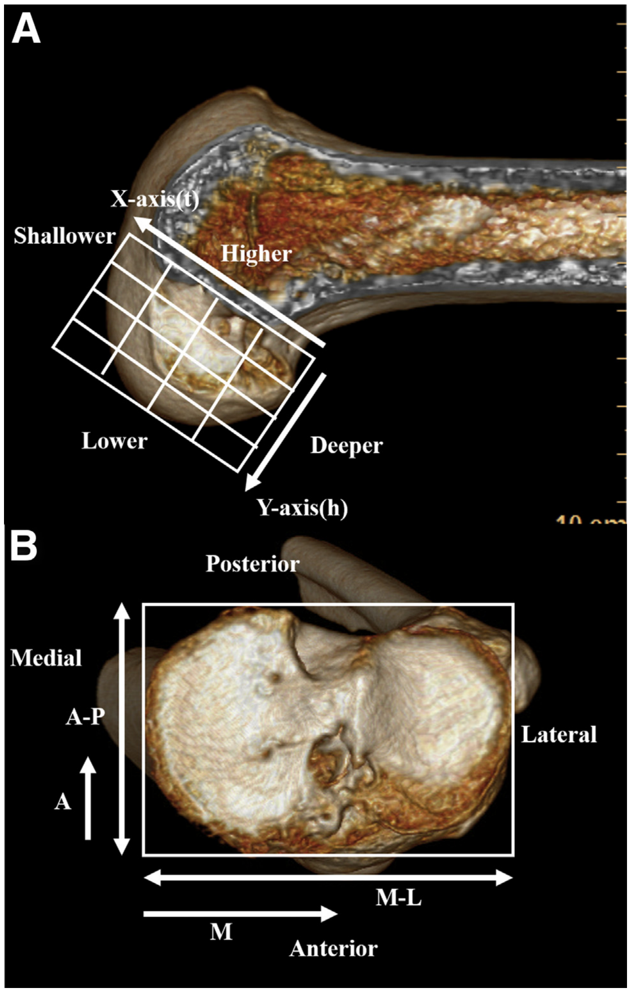

Fig 5. (A) The total sagittal diameter of the lateral femoral condyle is measured along the Blumensaat line (*x*-axis, *t*) and a line tangential to the Blumensaat line (*y*-axis, *h*). (B) A rectangular coordinate system for the tibia, for which the borders are located at the anterior-posterior (A-P) and medial-lateral (M-L) borders.

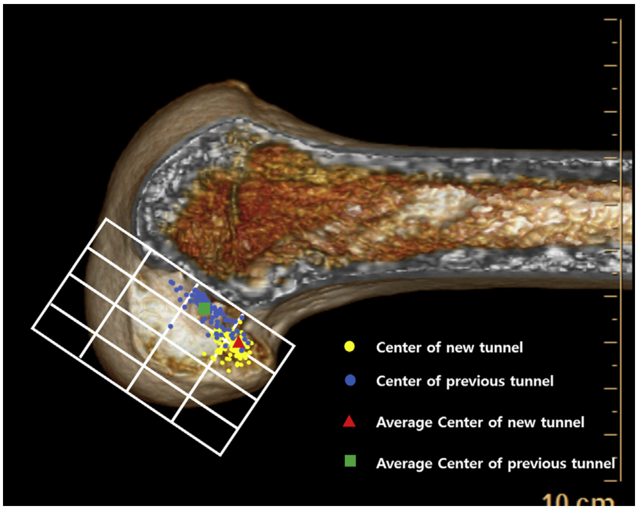

Fig 6. Center of the femoral tunnel based on the previous and new femoral tunnels, identified using the quadrant method.

complain of severe subjective knee instability and refused to undergo additional revisional surgery; hence, they were closely monitored and asked to perform knee exercises. None of the patients experienced stiffness after revision ACLR.

Discussion

The most important finding of this study was that the overlap of the femoral tunnel did not result in inferior clinical outcomes and stability in one-stage anatomical revision ACLR. These findings suggest that although approximately half of previous femoral tunnels interfered with new tunnel in one-stage revision ACLR, the clinical outcomes and stability of overlapped femoral tunnel group was comparable with those of non-overlapped group. One-stage anatomical revision ACLR using a single femoral tunnel was successful, regardless of femoral tunnel overlap. Although femoral tunnel overlap occurred in revision ACLR, it neither increased anterior laxity nor caused severe complications. As all previous tunnels were identified on preoperative CT or arthroscopy, complications of femoral tunnel overlap, such as wall breakage and severe widening of tunnel aperture, were avoided during revision ACLR.

Tunnel overlap could be expected or unexpected in various revision ACLR situations. In unexpected overlap, although a new tunnel is planned to completely avoid a previous tunnel, this does not always occur. In expected overlap, divergent tunnels are drilled and existing tunnels are re-reamed. Tunnel divergence is achieved using a different technique from that used in the primary procedure. The divergent tunnel technique can be attempted in patients with widening of an anatomically positioned tunnel with good bone quality. Re-reaming existing tunnels is indicated if the previous tunnel is positioned at the anatomical area without significant tunnel widening. We hypothesized that femoral tunnel overlap affects the clinical results of patients undergoing 1-stage revision ACLR. Therefore, we compared clinical results and stability between patients with overlapping and nonoverlapping femoral tunnels. However, no significant differences in clinical outcomes or stability were found. We did not compare clinical results and stability between patients with overlapping and nonoverlapping tibial tunnels because of the small sample size of the nonoverlapped tibial tunnel group (6%).

One-stage revision ACLR has the advantage of rapid recovery, fewer operative procedures, and restoration of knee stability without an ACL-deficient interval.[8] The objectives and patient subjective outcomes of 1-stage revision ACLR are comparable with those of 2-stage revision ACLR.[9] One-stage revision ACLR is not usually optimal in patients with tunnel widening and insufficient good bone stock.[7] Therefore, several studies have described techniques and materials that achieve secure graft fixation when the initial tunnel is malpositioned or widened in a 1-stage revision procedure.[19-21] In these studies, a freeze-dried allograft bone dowel, a biocomposite synthetic dowel graft, and bioactive moldable calcium phosphate cement were used for treating cylindrical bone defects. We performed 1-stage surgery using Achilles allo-bone or auto-iliac bone to manage the bone defect of the tibial tunnel. We also performed one-stage operation in cases of dilated and nonanatomically positioned femoral tunnels, thus minimizing the number of 2-stage revision ACLRs.

Choosing between 1- and 2-stage revision ACLR is difficult. Previous studies have recommended 2-stage ACLR if the tunnel size exceeded 12 to 14 mm.[7,8,22,23] Our indication of tunnel widening of >14 mm is in line with the previous indication for 2-stage ACLR. We performed 2-stage ACLR if the femoral tunnel was positioned in an anatomical area and showed a width of >14 mm. In cases of tibial tunnel widening of >14 mm, we performed 1-stage ACLR with a bone graft. Revision ACLR using a 1-stage tibial or femoral tunnel grafting technique resulted in improved clinical and stability outcomes.[1,4] These findings support our results of significantly improved clinical outcomes and stability with 1-stage ACLR.

Tunnel position significantly influenced ACLR failure, and malpositioning of the femoral tunnel is the most common cause of failed ACLR.[24,25] A biomechanical study reported that misplacement of the femoral tunnel is typically more anterior or vertical than its anatomical footprint.[26] In the Multicenter ACL Revision Study, a radiographic analysis found that 42% of femoral tunnels were >40% anterior to the femoral cortex.[27] If the femoral tunnel is >40% anterior to the Blumensaat line, it is considered "very anterior."[28] Misplacement of

Table 4. Comparison Between the Centers of the Pre-Existing and New Femoral Tunnels

Quadrant Method	Group NO (n = 52)	Group O (n = 41)	*P* value*
Previous femoral tunnel center, %			
x-axis	45.5 ± 7.5	33.2 ± 9.8	.001
y-axis	12.9 ± 6.1	17.9 ± 6.7	.007
New femoral tunnel center, %			
x-axis	21.5 ± 5.0	25.7 ± 4.9	<.001
y-axis	26.1 ± 8.1	22.3 ± 7.3	.020
New tibial tunnel center, %			
Anteroposterior	39.6 ± 9.5	39.7 ± 5.6	.925
Medial-lateral	46.6 ± 4.1	44.9 ± 2.6	.028

NOTE. Data are presented as means ± standard deviations unless otherwise indicated.

NO, nonoverlapped femoral tunnel; O, overlapped femoral tunnel.

*An independent *t* test as used to compare groups NO and O.

the tibial tunnel is typically more posterior and lateral with regard to the anatomical center.[29,30] In our study, tunnel overlapping occurred less often in the femoral tunnel, indicating that many femoral tunnels are positioned in a nonanatomical area. In revision ACLR, femoral tunnel overlap occurred in 44% of patients. However, most tibial tunnels (94%) were overlapped by a previous tunnel, indicating that a higher number of previous tibial tunnels were placed close to the anatomical area.

In revision ACLR, tunnel widening can interfere with graft fixation and healing, and tunnel widening with large bone defects presents a major challenge. Therefore, various surgical strategies exist for managing tunnel widening to allow initial secure graft fixation in revision ACLR. A technique using freeze-dried allograft bone dowels to fill cylindrical bone defects (diameter <16 mm) can be used to manage malpositioned and/or widened femoral tunnels.[31] Another technique for treating femoral bone voids in revision ACLR involves the use of a biocomposite synthetic dowel graft for treating isolated cylindrical defects of <11 mm.[19,31] We performed 1-stage revision ACLR with the Achilles allo-bone or auto-iliac bone graft technique for tibial tunnel widening of >14 mm. Femoral tunnel widening was managed with 2-stage revision ACLR. As 1-stage bone grafting at the femoral side was technically demanding, we performed 2-stage revision ACLR in cases of femoral tunnel widening of >14 mm in the anatomical area.

Although the new femoral tunnel overlapped the previous tunnel in revision ACLR, no significant differences in anterior laxity or clinical outcomes were found. This could be due to several reasons. First, in most instances, overlapping was well controlled during the operation because of direct visualization. Therefore, the overlapped area in the femoral tunnel was minimal. Second, severe complications such as tunnel fusion, wall breakage, fixation problems, and bone loss were identified immediately with arthroscopy, which allowed us to convert the procedure to 2-stage revision ACLR.

Limitations

Our study has several limitations. First, it was a retrospective and comparative study. As we did not select random treatment options for the patients in group O, we could not evaluate the actual effect of tunnel overlaps. If we treated one-half of these patients with bone grafts and 2-stage reconstruction, we could evaluate the actual effect of tunnel overlaps. Therefore, a randomized prospective study is needed to evaluate the exact effect of tunnel overlaps on clinical outcomes and stability. Second, the time from primary ACLR to graft failure differed significantly between the patients with nonoverlapping and overlapping tunnels. As the recent trend of femoral tunnel position became closer to the anatomical position, the tunnel overlapped group had primary ACLR more recently than the nonoverlapped group. The difference in the time from primary ACLR to graft failure was unavoidable using the present study design. However, we found no significant difference in time from failure to revision. Third, loss of patients to follow-up could have affected the results. Finally, the effects of tibial tunnel overlap and widening were not evaluated. Although we performed 1-stage revision ACLR in cases of tibial tunnel widening, the effect of tibial tunnel bone grafting was not evaluated. We also did not compare clinical results between the overlapped and nonoverlapped tibial tunnel groups. Additional tibial tunnel-related investigations and measurements are required to validate our findings.

Conclusions

One-stage anatomical revision ACLR significantly improved clinical results. Most tibial tunnels (94%) and approximately one-half (44%) of femoral tunnels overlapped. The overlapped femoral tunnel group did not show inferior outcomes or stability.

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