Outcomes After 1-Stage Versus 2-Stage Revision Anterior Cruciate Ligament Reconstruction

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Background: Revision anterior cruciate ligament reconstruction (ACLR) is becoming increasingly common as the number of primary ACLR cases continues to rise. Despite this, there are limited data on the outcomes of revision ACLR and even less information specifically addressing the differences in 1-stage revision reconstruction versus those performed in a 2-stage fashion after primary reconstruction.

Purpose: To compare the outcomes, patient satisfaction, and failure rates of 1-stage versus 2-stage revision ACLR.

Study Design: Cohort study; Level of evidence, 3.

Methods: All patients who underwent revision ACLR between 2010 and 2014 by a single surgeon were collected, and skeletally mature patients over the age of 17 years were included. Patients were excluded if they were skeletally immature; had a previous intra-articular infection in the ipsilateral knee; underwent a prior alignment correction procedure, cartilage repair or transplant procedure, or meniscal allograft transplantation; or had an intra-articular fracture. An ipsilateral or contralateral bone–patellar tendon–bone (BPTB) autograft was the graft of choice. A BPTB allograft was considered for patients aged $\geq$50 years, for any patient with an insufficient ipsilateral or contralateral patellar tendon, or for those who chose not to have the contralateral patellar tendon graft harvested. Patients completed a subjective questionnaire preoperatively and at a minimum of 2 years postoperatively. Magnetic resonance imaging and computed tomography of all knees were performed preoperatively to assess for associated injuries and to evaluate the ACLR tunnel size and location. Patients with malpositioned tunnels that would critically overlap with an anatomically placed tunnel or those with tunnels $\geq$14 mm in size underwent bone grafting.

Results: A total of 88 patients met the inclusion criteria for this study. There were 39 patients in the 1-stage revision surgery group (19 male, 20 female) and 49 patients in the 2-stage revision surgery group who underwent tunnel bone grafting first (27 male, 22 female). In both groups, the 12-item Short Form Health Survey (SF-12) Physical Component Summary, Western Ontario and McMaster Universities Arthritis Index, Lysholm, and Tegner activity scale scores significantly improved from preoperatively to postoperatively. There was no significant difference in the SF-12 Mental Component Summary score before and after surgery in either group. Furthermore, there was no significant difference in failure rates or other demographic data between the groups. We observed 4 failures in the 1-stage reconstruction group (10.3%) and 3 failures in the 2-stage reconstruction group (6.1%).

Conclusion: In this study, objective outcomes and subjective patient scores and satisfaction were not significantly different between 1-stage and 2-stage revision ACLRs. Both groups had significantly improved objective outcomes and patient subjective outcomes without notable differences in failure rates. Further longitudinal studies comparing 1-stage and 2-stage revision ACLRs over a longer time frame are recommended.

Keywords: anterior cruciate ligament; ACL; revision ACLR; knee; revision; staged

Anterior cruciate ligament (ACL) tears have been reported to account for up to half of all knee ligament surgeries.[21] ACL reconstruction (ACLR) rates have increased in frequency over the past 20 years to roughly 200,000 ACLRs each year.[27] As the number of primary ACLRs has continued to increase, the incidence of revision ACLRs has also increased to a rate of between 4.1% and 13.3% of all primary ACLRs performed.[32] Risk factors for primary ACLR failure broadly include incorrect tunnel placement, secondary trauma, undiagnosed concomitant knee injuries, failed graft healing, arthrofibrosis, and graft size or type.[3,11,12]

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Revision ACLR surgery can be mainly divided into 2 groups: 1-stage and 2-stage procedures.[13] One-stage revision ACLR is indicated when the initial femoral and tibial tunnels are correctly positioned, have not undergone tunnel widening or osteolysis, and will not converge with placement of the proposed new tunnels.[15] One-stage procedures allow for a more rapid recovery, fewer operative procedures, and the restoration of knee stability without an ACL-deficient interval.[8] However, in cases in which previous malpositioned reconstruction tunnels cannot be bypassed or there is significant reconstruction tunnel widening ($\geq$14 mm), a 2-stage procedure is considered.[8] Two-stage revision ACLR typically involves an initial bone graft procedure to fill the widened or misplaced tunnels, with a subsequent time allowance for the bone graft to heal sufficiently before the second stage of revision ACLR.[24]

The decision to perform 1-stage or 2-stage revision ACLR is based on the position and size of the reconstruction tunnels and is an important determination from both a surgeon and patient standpoint. For the surgeon, deciding to perform 2-stage revision surgery requires 2 separate but interdependent operative procedures. From a patient standpoint, 2-stage revision is a longer process, with 2 separate rehabilitation intervals and protocols, and requires more commitment from the patient. As a result, patient expectations should be managed accordingly. Furthermore, patients need to be educated on the differences between the 1-stage and 2-stage revision procedures, including the need for an extended time interval between procedures to allow for adequate bone graft healing in 2-stage revision ACLR.

To date, the literature on revision ACLR surgery has largely focused on comparing revision ACLR outcomes to primary ACLR outcomes. However, there is a paucity of studies looking specifically at revision ACLR cohorts that compare the outcomes of 1-stage versus 2-stage revision surgery. For the aforementioned reasons, the purpose of this study was to compare the outcomes, patient satisfaction, and failure rates of 1-stage versus 2-stage revision ACLR. We hypothesized that there would be no difference in the failure rates between 1-stage and 2-stage revision ACLRs but that the additional bone grafting procedure utilized in 2-stage revision ACLR would lead to reduced patient satisfaction and subjective outcomes despite providing clinically equal objective outcomes.

METHODS

Patient Selection

This study was approved by the institutional review board at our institution. This was a retrospective study of prospectively collected data. Patients were included in this study if they were over 17 years of age (with radiographically confirmed closed physes) and had either undergone 1-stage or 2-stage revision ACLR performed by a single surgeon (R.F.L.) between 2010 and 2014 with a minimum of 2 years of follow-up. All patients with failed ACLR underwent a detailed history, clinical examination, and radiographic workup to determine the cause of ACL graft failure. Patients were excluded from this study if they were skeletally immature; had a previous intra-articular infection or intra-articular fracture in the ipsilateral knee; or underwent a prior alignment correction procedure, cartilage repair or transplant procedure, or meniscal allograft transplantation. Patients were not excluded based on the number of ACLRs that they had previously undergone nor on the basis of concomitant injuries or procedures.

Indications for 1-Stage or 2-Stage Revision ACLR Surgery

Indications for 1-stage revision ACLR included a previous anatomic tunnel position on both the femoral and tibial ACL footprints, adequate femoral and tibial bone stock with contained tunnels, a previous reconstruction tunnel diameter less than 14 mm, or a previous tunnel sufficiently malpositioned so as to not interfere with the anatomic placement of a new tunnel. Indications for 2-stage revision ACLR included tunnel malpositioning that interfered with the placement of new anatomic tunnels, suboptimal bone stock or loss of tunnel containment, tunnel aperture $\geq$14 mm, and an inability to adequately place or secure the ACL graft during the initial proposed revision surgery. A schematic of the treatment algorithm used for each patient is shown in Figure 1.

To ensure appropriate indications for 1-stage or 2-stage revision ACLR, each patient underwent serial measurements of the previous reconstruction tunnel diameters on several sequences of plain radiographs, magnetic resonance imaging (MRI), and computed tomography (CT) (Figure 2). If the reconstruction tunnel diameter was $\geq$14 mm in any sequence that was in the desired anatomic tunnel location or would critically overlap with these tunnels, the patient was indicated for 2-stage revision ACLR to include arthroscopic debridement, hardware removal, and bone grafting of the previous reconstruction tunnels (Figure 3).

Surgical Technique

Surgery was performed with the patient under general anesthesia in a supine position. The remnant ACL graft and any associated scar tissue were debrided. For both 1-stage and 2-stage revision ACLRs, a bone–patellar tendon–bone (BPTB) autograft was chosen for all patients younger than 50 years of age with an intact patellar tendon. An ipsilateral or contralateral BPTB autograft was the graft of choice. A BPTB allograft was considered for patients aged $\geq$50 years, any patient with an insufficient ipsilateral or contralateral patellar tendon, or those who chose not to have the contralateral patellar tendon graft harvested.[9,14,16,29]

One-Stage Revision. For 1-stage revision ACLR, an accessory medial arthroscopic portal was made to localize the native ACL footprint. A bur hole was placed midway between the anteromedial and posterolateral bundle attachments and posterior to the lateral intercondylar ridge as a reference.[36,37] This landmark was typically

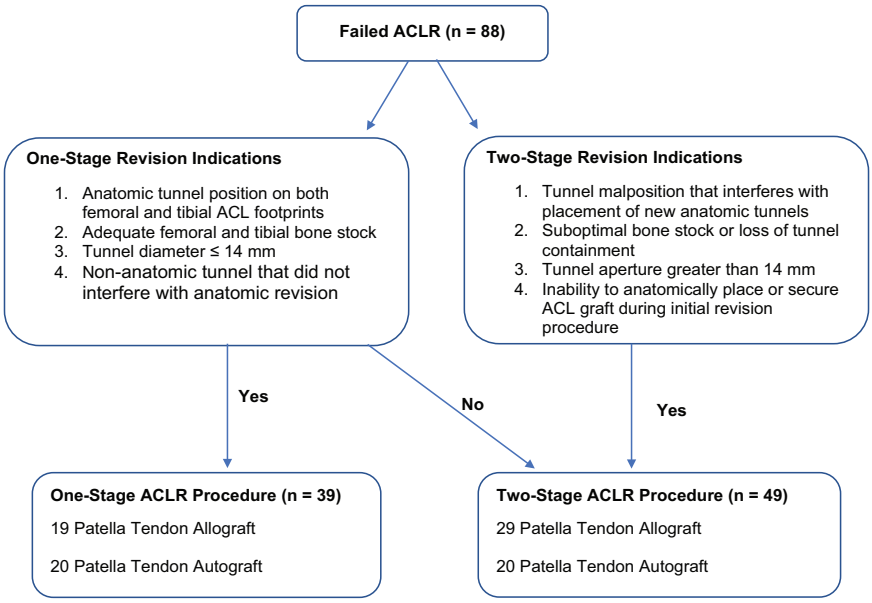

Figure 1. Treatment algorithm for patients presenting with failed anterior cruciate ligament reconstruction. All 4 criteria noted on the left of the figure were required for indicating the patient for 1-stage revision. If any of the criteria were not met, or if any of the 4 conditions noted on the right of the figure were encountered, 2-stage revision was considered.

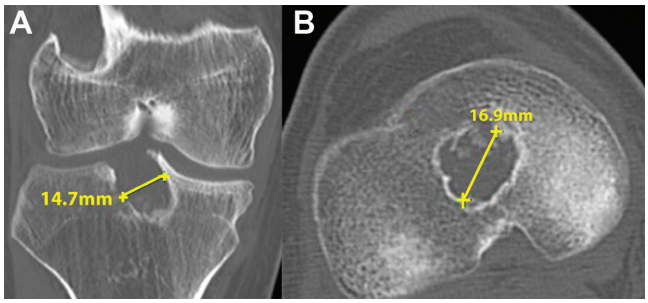

Figure 2. Computed tomography (CT) scan of a right knee demonstrating tunnel enlargement in the tibia including the corresponding diameter measurements in the (A) coronal and (B) axial planes of the tibia.

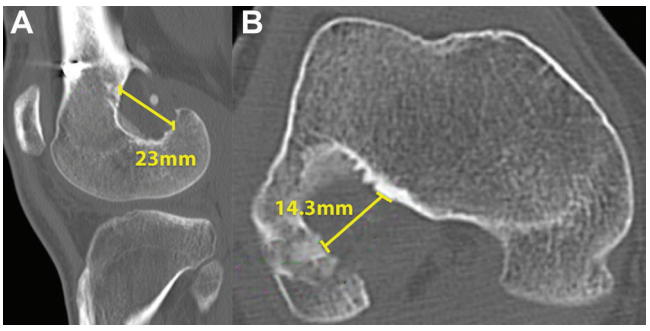

Figure 3. Computed tomography (CT) scan of a right knee demonstrating tunnel enlargement in the femur including the corresponding diameter measurements in the (A) sagittal and (B) axial planes of the femur. The widening of the femoral tunnel was ≥14 mm, and therefore, 2-stage revision was advocated.

visible only in cases of previous transtibial reconstruction or in cases with malpositioned tunnels in which the anatomic footprint on the femoral side remained intact. When the tunnel was found to be in a satisfactory position preoperatively, the tunnel entrance was used as the landmark.

The femoral and tibial tunnels were then prepared in the standard fashion utilizing the remnant stump of the ACL graft when available. If the ACL graft's tibial stump was unidentifiable, then the margins of the anterior insertion of the lateral meniscus were utilized to locate the tibial ACL attachment site.[36,37] The graft was then fixed into the femoral and tibial tunnels with a titanium interference screw, and of note, fixation of both the femoral and tibial ends of the ACL graft was performed in an anterograde fashion. Graft placement was verified arthroscopically, and the Lachman test confirmed that the graft had eliminated the pathological anterior translation.

Two-Stage Revision. Anterolateral and anteromedial arthroscopic ports were established, providing optimal visualization of the initial ACLR site. A potentially newly created revision ACL graft tunnel was believed to be present for a tunnel overlap of greater than 2 mm. If the tunnel was found to critically interfere with 1-stage revision, a series of shavers, rasps, and curettes were utilized to remove residual soft tissue from the failed femoral reconstruction tunnel. Articular cartilage and meniscal lesions were next treated. The femoral tunnel was prepared with the use of curettes, shavers, and rasps to remove soft tissue and hardware remnants. An incision was then made on the anteromedial tibia over the previous tibial tunnel to allow for the removal of previous fixation hardware. A guide wire

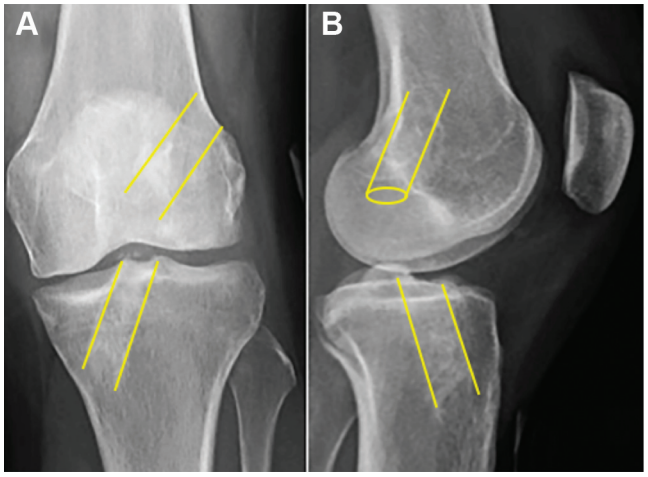

Figure 4. (A) Anteroposterior radiograph at 4 months postoperatively of a left knee showing the bone graft in place after 2-stage revision. (B) Lateral radiograph at 4 months postoperatively of the same patient showing placement of the bone graft into the anterior cruciate ligament graft tunnel after 2-stage revision .

was then drilled or placed by hand up the center of the tibial tunnel and held within the center of the tunnel with a small Kocher clamp to avoid eccentric reaming of the tibial tunnel. Finally, the tibial tunnel was reamed with a 10-mm acorn reamer. Any remaining soft tissue obstructing the tibial tunnel was removed, completing the preparation of the tunnel.[8] The Opteform allograft bone matrix (Exactech) was packed into both the femoral and tibial tunnels. The femoral tunnel was filled under arthroscopic guidance by packing the graft through a small, hemispherical plastic cannula (Arthrex), and the tibia was filled beginning at the distal aperture using the same cannula. The second operative procedure occurred at least 4 months after the first procedure after confirming adequate bone healing on follow-up anteroposterior and lateral radiographs. Postoperative bone graft radiographs are shown in Figure 4.

Rehabilitation

One-Stage Revision. All patients were allowed to bear weight on discharge and were told to use crutches for the first 4 weeks. Physical therapy commenced 24 hours after surgery to gain early range of motion and muscle reactivation and to control edema. Rehabilitation included straight-leg raises in an immobilizer until the patient was able to perform them without any extension sag. It was anticipated that patients would not return to full activities until a minimum of 9 months postoperatively.

Two-Stage Revision. After the bone graft procedure, patients were allowed to bear weight as tolerated and advised to use crutches for 2 weeks. After the first 2 weeks, patients remained in an ACL brace (CTi; Ossur) until the time of the second operative procedure. Rehabilitation after the second procedure followed the guidelines of the 1-stage revision procedure described previously. The main difference between rehabilitation in the case of standard ACLR versus 2-stage revision was the lack of progression to high-load muscular strength development and an increased time to return to sports activities.

Chondral and Meniscal Lesions

In both the 1-stage and 2-stage revision cohorts, intraoperative data regarding the location and type of any cartilaginous or meniscal lesions were collected prospectively at the time of surgery. Once a pre-existing injury was identified at either the first stage or second stage, it was classified as a chondral defect, meniscal lesion, or both. All patients undergoing 2-stage revision surgery were evaluated for pre-existing chondral and meniscal lesions, and any findings were compared with those found in the index bone grafting procedure. Meniscal tears were repaired whenever possible.

Patient Subjective Outcomes

The senior surgeon performed a complete physical examination during the follow-up at 2 and 6 weeks as well as at 3, 6, 12, and 24 months. Questionnaires were emailed to patients to obtain postoperative outcome scores. Patients completed a subjective questionnaire preoperatively and at a minimum of 2 years postoperatively, which included the Lysholm score,[4] Tegner activity scale,[4] Western Ontario and McMaster Universities Arthritis Index (WOMAC),[1] 12-item Short Form Health Survey (SF-12) Physical Component Summary (PCS) and Mental Component Summary (MCS), and patient satisfaction with outcomes. Patient satisfaction with outcomes was rated on a 10-point scale, with 1 equal to highly unsatisfied and 10 equal to highly satisfied. All patients were administered a questionnaire on a tablet at the time of the office visit or via email.

Graft Failure

Failure was defined as the need for additional surgery after either 1-stage or 2-stage revision ACLR and specifically included complete tears of the ACL graft seen on MRI combined with a patient clinical history and physical examination results compatible with reruptures of the graft. All complete failures, or partial tears with instability, were diagnosed preoperatively using a combination of physical examination findings and MRI. These injuries were confirmed with an examination under anesthesia, verified arthroscopically, and treated with revision ACLR surgery.

Statistical Analysis

Data were tested for normal distribution. Parametric methods were employed for comparisons between the cohorts for age and follow-up years. For comparisons of normally distributed continuous variables between cohorts, an independent t test was utilized. Nonparametric methods were employed for comparisons between the cohorts for the Lysholm score, Tegner activity scale, WOMAC, SF-12 PCS, SF-12 MCS, and patient satisfaction with outcomes.

TABLE 1
Patient Demographics and Graft Type by Surgical Group

	1-Stage Surgery (n = 39)	2-Stage Surgery (n = 49)	*P* Value
Sex, female/male, n	20/19	22/27	.495
Age, mean (range), y	32.4 (14.0-64.5)	30.4 (17.2-58.1)	.440
Body mass index, mean (range), kg/m^2	24.0 (16-36)	25.1 (18-49)	.412
Follow-up, mean (range), y	3.0 (2.0-5.6)	3.1 (2.0-5.0)	.774
Patellar tendon allograft, n	19	29	.32
Patellar tendon autograft, n	20 (20 ipsilateral)	20 (19 ipsilateral, 1 contralateral)	.32

For comparisons of nonnormally distributed continuous variables between cohorts, the Mann-Whitney *U* test was utilized. For preoperative and postoperative comparisons of dependent variables, the paired-samples *t* test was utilized for normally distributed data, and the Wilcoxon signed-rank test was utilized for nonnormally distributed data. Comparisons of 2 categorical data were performed using chi-square and Fisher exact tests. All *P* values were 2-tailed, and *P* values <.05 were considered statistically significant. All statistical analyses were performed with SAS version 9.4 (SAS Institute). There was no a priori power analysis performed because of the nature of the study, which was a retrospective comparative cohort design. This type of design and sample size may increase the chance of a type II error.

RESULTS

Demographics

A total of 88 patients met the inclusion criteria for this study with a minimum 2 years of follow-up. There were 39 patients in the 1-stage revision surgery group (19 male, 20 female) and 49 patients in the 2-stage revision surgery group (27 male, 22 female). Eighty-seven patients underwent their first revision procedure, and 1 patient in the 2-stage cohort had 3 failed ACLRs before presenting to the senior author (R.F.L.). Demographic data were documented at the initial clinical evaluation (Table 1). There were no significant differences between the groups for any demographic data. No patients who underwent 1-stage or 2-stage ACLR were lost to follow-up during the period of inclusion of this study. Furthermore, there were no additional patients who were identified as requiring revision surgery during the 2-year follow-up.

Graft Type

Nineteen patients in the 1-stage surgery group received patellar tendon allografts, while 20 patients received patellar tendon autografts. In the 2-stage surgery group, 29 patients received patellar tendon allografts, while 20 patients received patellar tendon autografts. The proportion of patients who received either graft type was not significantly different (*P* = .32). The graft type distribution is shown in Table 1.

TABLE 2
Preoperative and Postoperative Differences in Scores for Revision ACLR Groups[a]

	P Value From Preoperatively to Postoperatively	
	1-Stage Surgery	2-Stage Surgery
SF-12 PCS score	<.001[b]	<.001[b]
SF-12 MCS score	.323	.849
WOMAC total score	<.001[b]	<.001[b]
Lysholm score	<.001[b]	<.001[b]
Tegner activity scale score	<.001[b]	.002[b]

[a]ACLR, anterior cruciate ligament reconstruction; MCS, Mental Component Summary; PCS, Physical Component Summary; SF-12, 12-item Short Form Health Survey; WOMAC, Western Ontario and McMaster Universities Arthritis Index.
[b]Significant differences.

Outcomes

In both groups, the SF-12 PCS, WOMAC, Lysholm, and Tegner activity scale scores significantly improved from preoperatively to postoperatively. There was no significant difference in the SF-12 MCS score before and after surgery in either group (Table 2). There were no significant differences between 1-stage and 2-stage revision ACLRs for any objective or subjective outcomes (Table 3).

Concomitant Chondral or Meniscal Lesions

There were 39 patients in the 1-stage revision group and 49 patients in the 2-stage revision group. In the 1-stage surgery group, 4 patients had isolated chondral defects, 17 patients had isolated meniscal lesions, and 7 patients had both chondral and meniscal lesions. In the 2-stage surgery group, 41 patients had pre-existing chondral or meniscal lesions at the time of presentation for the 1-stage operative procedure. Isolated chondral injuries were identified in 15 patients (6 grade 3, 5 grade 4). An isolated meniscal lesion was seen in 11 patients, and 15 patients had both chondral and meniscal lesions. At the time of the second-stage operative procedure, 28 patients were found to have concomitant knee injuries. Chondral lesions were found in 12 patients (2 grade 3, 2 grade 4), meniscal lesions were observed in 6 patients, and 10 patients had both. Of the 12 chondral defects seen during the second-stage operative procedure, 7 lesions had persisted from the first operative procedure,

TABLE 3
Mean Alignment and Subjective Outcomes by Group[a]

	1-Stage Surgery	2-Stage Surgery	*P* Value
Coronal alignment	44.7 (12.5-82.5)	43.8 (21.4-71.7)	.750
Preoperative SF-12 PCS score	43.0 (27.0-64.0)	41.3 (28.0-58.0)	
Postoperative SF-12 PCS score	52.4 (30.5-60.9)	48.9 (24.2-65.4)	.081
Preoperative SF-12 MCS score	52.2 (22.0-69.0)	53.3 (28.0-69.0)	
Postoperative SF-12 MCS score	53.7 (30.1-65.4)	53.3 (19.5-68.1)	.822
Preoperative WOMAC total score	20.0 (0-64.0)	24.0 (0-54.0)	
Postoperative WOMAC total score	9.0 (0-92.0)	14.0 (19.5-68.1)	.163
Preoperative Lysholm score	58 (2-94)	58 (19-95)	
Postoperative Lysholm score	85 (68-100)	77 (27-100)	.170
Preoperative Tegner activity scale score[b]	3.1 (0-10.0)	3.5 (1.0-10.0)	
Postoperative Tegner activity scale score[b]	5.2 (2.0-10.0)	5.1 (0-10.0)	.873
Patient satisfaction	6.7 (1.0-10.0)	6.7 (1.0-10.0)	.788

[a]Values are reported as mean (range) unless otherwise indicated. MCS, Mental Component Summary; PCS, Physical Component Summary; SF-12, 12-item Short Form Health Survey; WOMAC, Western Ontario and McMaster Universities Arthritis Index.
[b]Values are reported as median (range).

TABLE 4
Pre-existing Knee Lesions in the 2-Stage Revision ACLR Group[a]

	First Stage–Identified Injury (n = 41)	Second Stage–Identified Injury (n = 28)
Chondral defect	15 (6 grade 3, 5 grade 4)	12 (2 grade 3, 2 grade 4)
Meniscal tear	11	6
Chondral defect + meniscal tear	15	10

[a]Values are reported as the number at the time of presentation for first-stage and second-stage procedures. ACLR, anterior cruciate ligament reconstruction.

TABLE 5
Number of Lesions Identified During the Second Stage That Were or Were Not Identified Previously

	Lesions That Persisted From First Stage	New Lesions Identified During Second Stage
Chondral defect	7	5
Meniscal tear	3	3
Chondral defect + meniscal tear	6	4

while 5 were newly identified lesions. Of the 6 meniscal tears identified during the second-stage operative procedure, 3 lesions persisted from the first operative procedure, and 3 were newly identified during the second operative procedure. Finally, of the 10 combined meniscal and chondral lesions seen at the second-stage procedure, 6 lesions had persisted from stage 1, while 4 lesions were newly identified during stage 2. A summary of concomitant injuries is shown in Table 4, and the timing of the identification of concomitant lesions is displayed in Table 5.

Failure Rates

There was no significant difference in the graft failure rate between groups ($P = .48$). Failure rates and characteristics are shown in Table 6. We observed 4 failures in the 1-stage revision group (10.3%) and 3 failures in the 2-stage revision group (6.1%). The mean time to failure for the patients with 1-stage surgery was 17 months (range, 4-46 months), and the mean time to failure for the patients with 2-stage surgery was 16 months (range, 3-42 months).

DISCUSSION

The most important finding of this study was that there was no difference in subjective outcomes or failure rates between the 1-stage and 2-stage revision ACLR groups. The lack of difference in subjective outcomes was unexpected because 2-stage revision ACLR involves 2 surgical procedures and a prolonged rehabilitation period. These findings suggest that although 2-stage revision reconstruction may predispose to additional intra-articular lesions and a longer surgical recovery, patients undergoing 2-stage revision ACLR may expect similar subjective outcomes at 2-year follow-up when compared with their counterparts undergoing 1-stage revision ACLR.

The decision to perform 1-stage or 2-stage revision ACLR is multifactorial. One-stage revision ACLR has been reported to be superior in patients with well-positioned tunnels, good bone stock, and hardware amenable to removal.[13,19] These findings support the outcomes in the present study and reinforce the previous findings by Carson et al,[7] demonstrating that appropriately selected patients undergoing 1-stage revision went on to have good outcomes and subjective scores at a minimum 2-year follow-up. Further, a recent biomechanical study of femoral fixation by Vaughn et al[33] supported the use of 1-stage

TABLE 6
Characteristics of Failed Revision and Subsequent Procedure Performed[a]

	Time From Index Procedure, mo	Resolution
1-stage failures		
Patient 1: graft failure, patient reported instability	6	Second revision ACLR surgery
Patient 2: graft failure, patient reported instability	46	Second revision ACLR surgery
Patient 3: graft failure, patient reported instability	12	Second revision ACLR surgery
Patient 4: graft failure, patient reported instability	4	Second revision ACLR surgery
2-stage failures		
Patient 1: MRI confirmed ACL tear after sports injury	3	Fourth revision ACLR surgery with patellar tendon autograft
Patient 2: Failed ACL graft with tunnel osteolysis	3	Second revision ACLR surgery with bone graft to both tunnels
Patient 3: Failed ACL graft with severe femoral and tibial osteolysis	42	Second revision ACLR surgery with bone graft to both tunnels

[a]ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MRI, magnetic resonance imaging.

revision in appropriately selected patients with adequate femoral bone stock and anatomic tunnels. In their study, there was no significant difference in initial graft strength between simulated BPTB autograft reconstruction performed with adjunctive femoral tunnel bone void filler and the control group.[33] These findings are also reflected in our study by the fact that our 1-stage revision group, which did not receive bone grafts, had comparable outcomes and subjective scores to those of the 2-stage revision group, which did receive bone grafts. Performing 2-stage reconstruction has a set of indications that have been loosely defined in the literature.[8,13,37] The indications outlined in these studies are comparable with the indications devised by the senior author. The senior author's indications for 1-stage or 2-stage revision are displayed in Figure 1.

Werner et al[34] published a study of 16 patients with ACL tunnel osteolysis who underwent 1-stage revision ACLR with placement of an allograft bone dowel in the femoral tunnel. This study found comparable outcomes to other 1-stage revision ACLR techniques and 2-stage revision[34]; however, these results are only applicable to isolated femoral bony deficiencies and not more extensive bony deficiencies. The findings of Werner et al[34] support our findings but also offer a dichotomy in technique, as we used titanium screw fixation for the final graft and a malleable allograft bone matrix (Opteform) to address bony deficiencies in 2-stage revision at both the femoral and tibial tunnels. Using the malleable bone matrix technique eliminates the need to precisely size the dowel bone graft, the need to ream out normal bone to fit the dowel graft, and the possibility of the dowel causing future tunnel expansion.

The most challenging decision regarding indications for most 1-stage or 2-stage revision ACLRs relates to the importance of tunnel orientation and aperture size. The previous literature has reported that if the tunnel size exceeds 12 to 14 mm, 2-stage surgery should be performed. Our threshold of 14 mm of tunnel widening falls within the range of previous studies that recommended 2-stage surgery if the tunnel diameter is greater than 12 to 14 mm.[2,8,13,17,22,36] Additional indications for 2-stage revision are poor bone stock, active infections, or hardware that cannot be removed during 1-stage revision.[8,35] Erickson et al[13] and Wilde et al[35] both demonstrated comparable results in patients who underwent 2-stage revision ACLR compared with those who underwent 1-stage reconstruction. These findings reinforce our results of significantly improved subjective outcomes from preoperatively to postoperatively within the 2-stage surgery group without a significant difference in graft failure or subjective outcomes between the 1-stage and 2-stage revision ACLR cohorts.

As previously highlighted, the tunnel size and orientation have been reported to have a significant effect on primary ACLR success rates. In our study, patients with a significant enlargement in tunnel size and/or nonanatomic orientation that interfered with anatomic reconstruction tunnel placement underwent 2-stage surgery. This decision is supported by existing studies that have reported tunnel malpositioning as the largest contributor to revision graft failure.[10,31] If tunnel placement and dimensions are found to be acceptable during the preoperative evaluation, they can likely be utilized during 1-stage revision. If the tunnel size or position prevents proceeding with 1-stage revision, the placement of a bone graft at the first stage allows for later anatomic tunnel placement through newly formed bone at the time of the second-stage operative procedure.

We found no significant difference in failure rates between the 1-stage and 2-stage revision ACLR groups. In this study, failure was defined as the need for subsequent surgery after 1-stage reconstruction or 2-stage reconstruction. The indications for revision were a complete rupture of a prior ACLR confirmed on MRI, or with physical examination demonstrating a positive Lachman or a grade 2 or 3 pivot shift examination. Our indications were similar to those reported in previous studies, which defined failure as including either a >6-mm increase in anterior-posterior displacement on the KT-1000 arthrometer, a positive Lachman test finding, and/or a grade 2 or 3 pivot shift.[18,25,28] Our observed failure rate in the 1-stage revision group was 10.3%. Our observed failure rate is comparable with that in a study by Noyes and Barber-Westin,[24]

who reported a 19% failure rate in their revision ACLR cohort. Moreover, additional studies have reported failure rates of 33%[26] and 36%[19] for 1-stage revision ACLR, and overall, our failure rate was improved or comparable with these previous studies.[19,24,26] We also observed a failure rate of 6.1% in the 2-stage revision ACLR group. This failure rate was comparable with that in a study by Thomas[30] that had reported a 2% failure rate in the 2-stage revision cohort. These findings reflect that although 2-stage revision is more technically challenging and involves more rehabilitation for the patient, there is no increased risk of failure in these patients.

Concomitant Outerbridge[6] grade 3 or 4 chondral lesions have been reported to produce worse outcomes in revision ACLR surgery,[23] and recent studies reported that patients with any associated chondral or meniscal injury who required partial meniscectomy, notchplasty, or microfracture had worse outcomes in revision ACLR surgery.[6,16] The finding that approximately 60% of the patients in our 1-stage revision cohort had chondral lesions was comparable with that of prior studies.[20,24,26] We also found a decrease in the number of new chondral lesions between the 1-stage and 2-stage revision groups. This finding is possibly because of the treatment of lesions at the time of the initial revision procedure. Despite the majority of patients having such lesions, and although these were moderately different between cohorts, such lesions did not appear to have an effect on patient outcomes between the 2 cohorts.

This study is not without limitations. Specifically, the indications for 1-stage and 2-stage revision reconstructions differ, and therefore, the cohorts in the preoperative period cannot be considered equal. Furthermore, a proportion of our patients had concomitant knee injuries including chondral defects and meniscal tears. These coexisting injuries may affect the trajectory of patient outcomes for both 1-stage and 2-stage revision ACLRs. Moreover, these injuries contribute to heterogeneity between the groups, which makes intercohort comparisons more challenging. Examining our results, the proportion of chondral defects remained stable between the first stage and second stage. This may be attributable to insufficient time between procedures to result in further cartilage wear. The rate of meniscal tears decreased from the first stage to the second stage. This was likely because of meniscal repair or meniscectomy being performed during the first-stage procedure when indicated. Finally, because the patients in this series were treated at a tertiary referral center, the number of staged revisions was likely increased compared with nonreferral centers with a similar surgical volume.

CONCLUSION

In this study, objective outcomes and subjective patient scores and satisfaction were not significantly different between 1-stage and 2-stage revision ACLR surgeries. Both groups had significantly improved objective outcomes and patient subjective outcomes without notable differences in failure rates. Further longitudinal studies comparing 1-stage and 2-stage revision ACLRs over a longer time frame are recommended.

REFERENCES

1. Bellamy N, Wilson C, Hendrikz J. Population-based normative values for the Western Ontario and McMaster (WOMAC) Osteoarthritis Index: part I. *Semin Arthritis Rheumatism*. 2011;41(2):139-148.
2. Bhatia S, Korth K, Van Thiel GS, et al. Effect of tibial tunnel diameter on femoral tunnel placement in transtibial single bundle ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(1):51-57.
3. Borchers JR, Kaeding CC, Pedroza AD, et al. Intra-articular findings in primary and revision anterior cruciate ligament reconstruction surgery: a comparison of the MOON and MARS Study Groups. *Am J Sports Med*. 2011;39(9):1889-1893.
4. Briggs KK, Lysholm J, Tegner Y, Rodkey WG, Kocher MS, Steadman JR. The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. *Am J Sports Med*. 2009;37(5):890-897.
5. Brophy RH, Haas AK, Huston LJ, Nwosu SK, Wright RW. Association of Meniscal Status, Lower Extremity Alignment, and Body Mass Index With Chondrosis at Revision Anterior Cruciate Ligament Reconstruction. *Am J Sports Med*. 2015;43(7):1616-1622.
6. Cameron ML, Briggs KK, Steadman JR. Reproducibility and reliability of the Outerbridge classification for grading chondral lesions of the knee arthroscopically. *Am J Sports Med*. 2003;31(1):83-86.
7. Carson EW, Anisko EM, Restrepo C, Panariello RA, O'Brien SJ, Warren RF. Revision anterior cruciate ligament reconstruction: etiology of failures and clinical results. *J Knee Surg*. 2004;17(3):127-132.
8. Chahla J, Dean CS, Cram TR, et al. Two-stage revision anterior cruciate ligament reconstruction: bone grafting technique using an allograft bone matrix. *Arthrosc Tech*. 2016;5(1):e189-e195.
9. Chang SK, Egami DK, Shaieb MD, Kan DM, Richardson AB. Anterior cruciate ligament reconstruction: allograft versus autograft. *Arthroscopy*. 2003;19(5):453-462.
10. Chen JL, Allen CR, Stephens TE, et al. Differences in mechanisms of failure, intraoperative findings, and surgical characteristics between single- and multiple-revision ACL reconstructions: a MARS cohort study. *Am J Sports Med*. 2013;41(7):1571-1578.
11. Conte EJ, Hyatt AE, Gatt CJ, Dhawan A. Hamstring autograft size can be predicted and is a potential risk factor for anterior cruciate ligament reconstruction failure. *Arthroscopy*. 2014;30(7):882-890.
12. Duffee A, Magnussen RA, Pedroza AD, Flanigan DC, Kaeding CC. Transtibial ACL femoral tunnel preparation increases odds of repeat ipsilateral knee surgery. *J Bone Joint Surg Am*. 2013;95(22):2035-2042.
13. Erickson BJ, Cvetanovich G, Waliullah K, et al. Two-stage revision anterior cruciate ligament reconstruction. *Orthopedics*. 2016;39(3):e456-e464.
14. Foster TE, Wolfe BL, Ryan S, Silvestri L, Kaye EK. Does the graft source really matter in the outcome of patients undergoing anterior cruciate ligament reconstruction? An evaluation of autograft versus allograft reconstruction results: a systematic review. *Am J Sports Med*. 2010;38(1):189-199.
15. Franceschi F, Papalia R, Del Buono A, et al. Two-stage procedure in anterior cruciate ligament revision surgery: a five-year follow-up prospective study. *Int Orthop*. 2013;37(7):1369-1374.
16. Harner CD, Olson E, Irrgang JJ, Silverstein S, Fu FH, Silbey M. Allograft versus autograft anterior cruciate ligament reconstruction: 3- to 5-year outcome. *Clin Orthop Relat Res*. 1996;324:134-144.
17. Hofbauer M, Muller B, Murawski CD, Baraga M, van Eck CF, Fu FH. Strategies for revision surgery after primary double-bundle anterior cruciate ligament (ACL) reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(9):2072-2080.
18. Johnson DL, Fu FH. Anterior cruciate ligament reconstruction: why do failures occur? *Instr Course Lect*. 1995;44:391-406.
19. Johnson DL, Swenson TM, Irrgang JJ, Fu FH, Harner CD. Revision anterior cruciate ligament surgery: experience from Pittsburgh. *Clin Orthop Relat Res*. 1996;325:100-109.
20. Johnson WR, Makani A, Wall AJ, et al. Patient outcomes and predictors of success after revision anterior cruciate ligament reconstruction. *Orthop J Sports Med*. 2015;3(10):2325967115611660.
21. Lynch TS, Parker RD, Patel RM, Andrish JT, Spindler KP. The impact of the Multicenter Orthopaedic Outcomes Network (MOON) research

on anterior cruciate ligament reconstruction and orthopaedic practice. *J Am Acad Orthop Surg*. 2015;23(3):154-163.
22. Magnussen RA, Debieux P, Benjamin B, et al. A CT-based classification of prior ACL femoral tunnel location for planning revision ACL surgery. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(7):1298-1306.
23. MARS Group. Meniscal and articular cartilage predictors of clinical outcome after revision anterior cruciate ligament reconstruction. *Am J Sports Med*. 2016;44(7):1671-1679.
24. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. *Am J Sports Med*. 2006;34(4):553-564.
25. Noyes FR, Barber-Westin SD. Revision anterior cruciate surgery with use of bone-patellar tendon-bone autogenous grafts. *J Bone Joint Surg Am*. 2001;83(8):1131-1143.
26. Noyes FR, Barber-Westin SD, Roberts CS. Use of allografts after failed treatment of rupture of the anterior cruciate ligament. *J Bone Joint Surg Am*. 1994;76(7):1019-1031.
27. Ohly NE, Murray IR, Keating JF. Revision anterior cruciate ligament reconstruction: timing of surgery and the incidence of meniscal tears and degenerative change. *J Bone Joint Surg Br*. 2007;89(8):1051-1054.
28. Samitier G, Marcano AI, Alentorn-Geli E, Cugat R, Farmer KW, Moser MW. Failure of anterior cruciate ligament reconstruction. *Arch Bone Joint Surg*. 2015;3(4):220-240.
29. Singhal MC, Gardiner JR, Johnson DL. Failure of primary anterior cruciate ligament surgery using anterior tibialis allograft. *Arthroscopy*. 2007;23(5):469-475.
30. Thomas NP. Revision anterior cruciate ligament reconstruction using a 2-stage technique with bone grafting of the tibial tunnel. *Am J Sports Med*. 2005;33(11):1701-1709.
31. Trojani C, Sbihi A, Djian P, et al. Causes for failure of ACL reconstruction and influence of meniscectomies after revision. *Knee Surg Sports Traumatol Arthrosc*. 2010;19(2):196-201.
32. van Eck CF, Schkrohowsky JG, Working ZM, Irrgang JJ, Fu FH. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. *Am J Sports Med*. 2012;40(4):800-807.
33. Vaughn ZD, Schmidt J, Lindsey DP, Dragoo JL. Biomechanical evaluation of a 1-stage revision anterior cruciate ligament reconstruction technique using a structural bone void filler for femoral fixation. *Arthroscopy*. 2009;25(9):1011-1018.
34. Werner BC, Gilmore CJ, Hamann JC, et al. Revision anterior cruciate ligament reconstruction: results of a single-stage approach using allograft dowel bone grafting for femoral defects. *J Am Acad Orthop Surg*. 2016;24(8):581-587.
35. Wilde J, Bedi A, Altchek DW. Revision anterior cruciate ligament reconstruction. *Sports Health*. 2014;6(6):504-518.
36. Wolf BR, Ramme AJ, Wright RW, et al. Variability in ACL tunnel placement: observational clinical study of surgeon ACL tunnel variability. *Am J Sports Med*. 2013;41(6):1265-1273.
37. Ziegler CG, Pietrini SD, Westerhaus BD, et al. Arthroscopically pertinent landmarks for tunnel positioning in single-bundle and double-bundle anterior cruciate ligament reconstructions. *Am J Sports Med*. 2011;39(4):743-752.