Systematic Review

Consistent Indications and Good Outcomes Despite High Variability in Techniques for Two-Stage Revision Anterior Cruciate Ligament Reconstruction: A Systematic Review

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Purpose: To systematically review the current literature regarding the indications, techniques, and outcomes after 2-stage revision anterior cruciate ligament reconstruction (ACLR). **Methods:** A literature search was performed using SCOPUS, PubMed, Medline, and the Cochrane Central Register for Controlled Trials according to the 2020 Preferred Reporting Items for Systematic Reviews and Meta Analyses statement. Inclusion criteria was limited to Level I-IV human studies reporting on indications, surgical techniques, imaging, and/or clinical outcomes of 2-stage revision ACLR. **Results:** Thirteen studies with 355 patients treated with 2-stage revision ACLR were identified. The most commonly reported indications were tunnel malposition and tunnel widening, with knee instability being the most common symptomatic indication. Tunnel diameter threshold for 2-stage reconstruction ranged from 10 to 14 mm. The most common grafts used for primary ACLR were bone−patellar tendon−bone (BPTB) autograft, hamstring graft, and LARS (polyethylene terephthalate) synthetic graft. The time elapsed from primary ACLR to the first stage surgery ranged from 1.7 years to 9.7 years, whereas the time elapsed between the first and second stage ranged from 21 weeks to 13.6 months. Six different bone grafting options were reported, with the most common being iliac crest autograft, allograft bone dowels, and allograft bone chips. During definitive reconstruction, hamstring autograft and BPTB autograft were the most commonly used grafts. Studies reporting patient-reported outcome measures showed improvement from preoperative to postoperative levels in Lysholm, Tegner, and objective International Knee and Documentation Committee scores. **Conclusions:** Tunnel malpositioning and widening remain the most common indications for 2-stage revision ACLR. Bone grafting is commonly reported using iliac crest autograft and allograft bone chips and dowels, whereas hamstring

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autograft and BPTB autograft were the most used grafts during the second-stage definitive reconstruction. Studies showed improvements from preoperative to postoperative levels in commonly used patient reported outcomes measures. **Level of Evidence:** IV, systematic review.

Anterior cruciate ligament reconstruction (ACLR) has remained the gold-standard treatment for anterior cruciate ligament (ACL) tears for the past 40 years,[1] with continued growth in the number of ACLRs performed annually worldwide over the past 20 years.[2-5] ACLR is recommended for athletes and highly active patients engaging in dynamic knee movements or in patients with functional instability, whereas conservative treatment of ACL injuries may be sufficient in nonathletes.[6,7] Despite the high reported rate of patient satisfaction and restoration of knee stability, primary ACLR has a failure rate ranging between 2.0% and 4.1%.[8] The most commonly identified cause of surgical failure include tunnel malpositioning, along with the occurrence of missed meniscal injuries, new injuries, inadequate fixation, and poor postoperative rehabilitation.[9,10] Relative to primary ACLR, revision ACLR tends to have less-predictable outcomes, often yielding lower patient-reported scores, residual laxity, and greater complication rates.[11,12] Revision ACLR can be further complicated by a high rate of concomitant chondral and meniscal injuries in patients with failed primary reconstruction.[13-15]

Revision ACLR can be performed either in a 1- or 2-stage approach. A 1-stage revision is preferred by many surgeons,[16] as it avoids the need for a second anesthesia and timing between index and definitive procedures in which the ACL remains deficient.[14,17] Two-stage ACLR is performed in an estimated 8% to 9% of revision cases and generally indicated when a bone-grafting procedure is required to address tunnel widening, when tunnel convergence might be unavoidable or when additional procedures are required to address malalignment or meniscal deficiency.[18] A recent meta-analysis by Colatruglio et al.[19] observed no difference when comparing outcomes between 1-stage and 2-stage revision ACLR; however, this study was limited to primarily retrospective and noncomparative investigations.

As a result of the relatively infrequent reporting of 2-stage revision ACLR procedures, details regarding indications, especially the threshold for tunnel widening, along with technique and outcomes, remain limited. Furthermore, there remains no consensus regarding the technical aspects of treatment, such as preferred bone graft source and length of time between surgical stages. As such, the purpose of this study was to systematically review the current literature regarding the indications, techniques, and outcomes after 2-stage revision ACLR. The authors hypothesized that the primary indications from 2-stage revision ACLR would be persistent instability secondary to tunnel malpositioning, whereas bone grafting would be commonly used to allow for bony integration, with improved outcomes reported after definitive reconstruction.

Methods

A systematic review was conducted according to the 2020 Preferred Reporting Items for Systematic Reviews and Meta Analyses statement.[20] A literature search identifying studies reporting indications, techniques, and outcomes of 2-stage revision ACLR was conducted on June 29, 2022, using PubMed, MEDLINE, Scopus, the Cochrane Database for Systematic Review, and the Cochrane Central Register for Controlled Trials. The search included a combination of the following terms combined with Boolean operators: "ACL," "anterior cruciate ligament," "reconstruction," "revision," "staged," "two-stage," "two-staged," "two-step," "multi-stage," "bone dowel," "bone graft," "bone plug," "tunnel," "outcomes."

Eligibility Criteria

Inclusion criteria consisted of Level I-IV studies written in English or with English-translation, reporting on human patients undergoing 2-stage revision ACLR with reported indications, surgical techniques, imaging, and/or clinical outcomes. The exclusion criteria consisted of non-English language studies, review articles, technical notes, case reports, editorial commentaries, biomechanical and animal studies, epidemiologic and national database studies, studies reporting on patients undergoing primary ACLR, studies combining outcomes after 1-stage and 2-stage revision ACLR, studies reporting on patients undergoing realignment procedures (eg, anterior closing wedge osteotomy, distal femoral osteotomy, high tibial osteotomy, and tibial tubercle osteotomy), chondral restoration procedures (eg, osteochondral allograft transplantation, osteochondral autograft transplantation, and autologous chondrocyte implantation), as well as studies including patients younger than the age of 18 years. Patients undergoing chondral debridement, microfracture, meniscal debridement, or meniscal repair were included in our analysis, while patients undergoing meniscal allograft transplantation were excluded.

Data Extraction

A medical student (V.G.) and a resident (F.J.C.) independently performed an initial title and abstract

		A clearly stated aim	Inclusion of consecutive patients	Prospective collection of data	Endpoints appropriate to the aim of the study	Unbiased assessment of the study endpoint	Follow-up period appropriate to the aim of the study	Loss to follow up less than 5%	Prospective evaluation of the study size	A control group having the gold standard intervention	Contemporary groups	Baseline equivalence of groups	Statistical analysis adapted to the study design	Total
Buyukdogan et al.		2	2	2	2	0	2	1	0	-	-	-	-	11
Diermeier et al.		2	2	0	2	0	2	1	0	0	2	0	2	13
Franceschi et al.		2	2	2	2	0	2	2	0	-	-	-	-	12
Grote et al.		2	1	2	2	0	1	2	0	-	-	-	-	10
Mitchell et al.		2	2	0	2	0	2	2	1	1	2	2	2	18
Prall et al.		2	2	2	2	0	1	2	0	-	-	-	-	11
Theodorides et al.		2	2	0	1	0	1	1	0	-	-	-	-	7
Thomas et al.		2	2	2	2	0	2	2	2	2	2	2	2	22
Uchida et al.		2	2	2	2	0	1	2	0	-	-	-	-	11
Van de Pol et al.		2	1	2	2	0	1	2	0	-	-	-	-	10
Van Tol et al.		2	2	0	2	1	2	2	0	-	-	-	-	11
Ventura et al.		2	1	0	2	0	2	2	0	-	-	-	-	9
Von Recum et al.		2	2	2	2	2	2	2	2	2	2	2	2	24

Figure 2. Risk of bias assessment using the MINORS criteria

Fig 1. Risk of bias assessment using the MINORS criteria. (MINORS, Methodological Index for Non-Randomized Studies.)

screening, followed by a full-text screening to determine whether the inclusion or exclusion criteria were met. Any disagreements during screening were discussed and decided by an attending orthopaedic surgeon (E.S.M.), during which time no disagreements were encountered. Reference lists from the included studies were reviewed and reconciled to ensure that all relevant studies meeting inclusion criteria were identified.

Study characteristics from each article were extracted and included: journal of publication, year published, level of evidence, patient demographics (age, sex), follow-up, and time from the index ACLR. Information regarding mechanisms, mode of primary ACLR failure, and indications for the 2-stage approach were recorded. Surgical techniques in each study were assessed and data was recorded regarding the performance of bone grafting, bone grafting source, time between first and second stage, second-stage graft source, and tibial/femoral fixation of the graft during the second stage. Any reported data from radiographs and advanced imaging (magnetic resonance imaging, computed tomography [CT]), was gathered and grouped based on time-point along the 2-stage procedure (preoperative, postoperative first stage, postoperative second stage). All reported clinical outcomes scores were recorded, as well as the incidence of any reported complications related to either stage of surgery.

Risk of Bias

To ensure bias was minimized, a methodological quality assessment was performed by 2 independent authors (V.G. and F.J.C.) using the Methodological Index for Non-Randomized Studies (MINORS) criteria.[21] Any disagreements were resolved by a third investigator (E.S.M.) if an assigned score of >2 was encountered. The MINORS is a numerical scale used for noncomparative, nonrandomized studies. The criteria consist of 12 questions, with each question scored with a 0 if not reported, 1 if reported but inadequate, or 2 if reported and adequate. The ideal score for noncomparative, nonrandomized studies is 24. All 13 studies included in this review were assessed with the MINORS criteria (Fig 1). The mean MINORS score was 13 ± 5.12 (range, 7-24). For noncomparative studies, the mean score was 10.2 ± 1.5 (range, 7-12), whereas the mean score for comparative studies was 19.25 ± 4.9 (range, 13-24).

Data Analysis

Study characteristics and patient demographics information was gathered and analyzed with Microsoft Excel (Version 2206; Microsoft Corp., Redmond, WA). Weighted pooled means and standard deviations were calculated based on the patient population of the respective studies. When preoperative and postoperative patient-reported outcome measures were

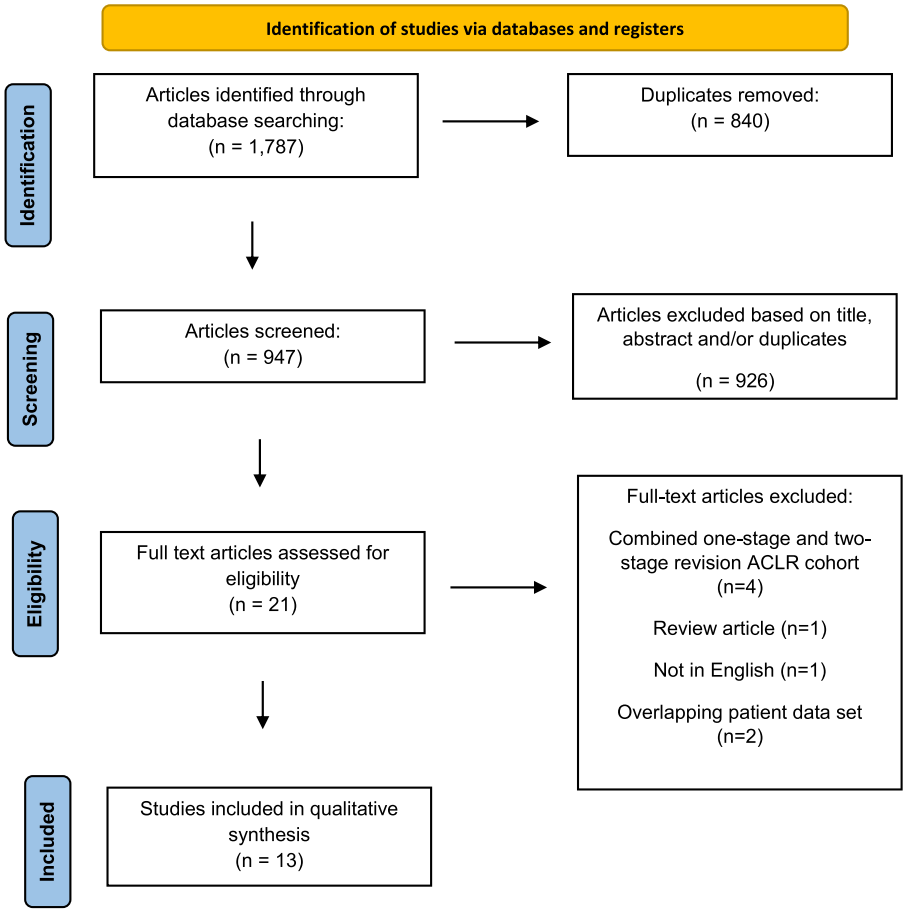

Fig 2. Preferred Reporting Items and Meta-Analysis flowchart showing selection criteria of identified studies. (ACLR, anterior cruciate ligament reconstruction.)

reported, the mean improvement was calculated. Studies reporting clinical outcomes with median and range were converted to mean and standard deviation via the VassarStats calculator from Hozo et al.[22] All forest plots were produced via Open Meta-Analyst (Version 12.11.14, Tufts University, Boston, MA).[23] Objective International Knee and Documentation Committee (IKDC) scores were transformed into dichotomous variables. A positive score was defined as A or B and a negative score was defined as C or D. An inverse variance model was used to compare objective IKDC scores.

Results

The initial literature search identified a total of 1,787 entries (Fig 2). After duplicates were removed, 947 articles remained and underwent title and abstract screening. Twenty-one articles were then selected to undergo full-text review. Following full-text review, 13 studies, with a total sample size consisting of 355 patients, were found to meet inclusion criteria and were included in this review (Table 1).

Patient sex was reported in 11 studies. The majority of patients were male in 10 studies, whereas 1 study consisted of 3 female and 2 male patients.[24] The mean time from the primary ACLR to the first stage of revision ACLR was reported in 7 studies,[24-30] ranging from 1.7 years to 9.7 years. The most common primary ACLR grafts were bone–patellar tendon–bone (BPTB) autograft,[25-27,30,31] hamstring graft,[24,25,27,30,31] and LARS artificial graft.[29,31] Mean final follow-up after the second stage of revision ACLR was reported in 12 studies, ranging from 12 months[24] to 6.7 years.[26]

Indications

The most common symptomatic indication for revision ACLR was knee instability, reported in 12 studies consisting of 318 patients. In 7 studies (n = 191 patients) anterior knee laxity was confirmed with a positive Lachman and positive pivot shift test.[16,24,26-29,31] Tunnel widening was as an indication for 2-stage revision ACLR in 9 studies.[16,24,25,27,28,30,32-34] Thresholds for tunnel widening warranting revision ACLR ranged from greater than 14 mm,[16,25,33] greater than 12 mm,[28,32] and greater than 10 mm,[30,34] whereas Uchida et al.[27] required a tibial tunnel aperture of >20mm as indication for two-stage revision ACLR. Tunnel malposition was a reported indication in ten studies.[16,24,25,27,28,30-34] Tunnel malposition was related to nonanatomically placed tunnels, primary tunnels

Table 1. Overview of Included Studies

Study	Journal (Year)	LOE	No. of Patients	Mean Patient Age (Range), y	Sex (Male/ Female)	Indications for 2-Stage Procedure	Mechanisms (No. of Patients)	Concomitant Injuries (No. of Patients)	Concomitant Procedures (No. of Patients)	Mean Follow-Up (Range)
Buyukdogan et al.[25]	*Arthroscopy* (2021)	4	21	32.1 (19-50)	13 M/8 F	Tunnel widening (>14 mm), primary tunnel overlap with desired tunnels	Repeat trauma (11), Instability (10)	NR	Partial meniscectomy (3), loose body removal (1), hardware removal (10)	2.6 y
Diermeier et al.[32]	*BMC Musculoskeletal Disorders* (2018)	3	44	30.5 (16.7-49.4)	13 M/31 F	Tunnel widening (>12 mm), suboptimal bone stock, inability to place new tunnel	NR	Meniscus lesion (19), cartilage defect (10), patellofemoral cartilage defect (10)	NR	33.9 mo (8-68)
Franceschi et al.[26]	*International Orthopaedics* (2013)	4	30	29.1	19 M/11 F	NR	Direct impact (8), indirect impact (7), pivoting activity (9), MVA (3), other (3)	Grade 1/2 cartilage defect (12)	Medial meniscectomy (10), lateral meniscectomy (8)	6.7 y (5-9)
Grote et al.[24]	*Knee* (2015)	3	5	27.6	2 M/3 F	Tunnel widening and femoral tunnel placement	Tunnel misplacement (3), infection (1), sports (1)	NR	NR	12 mo
Mitchell et al.[16]	*American Journal of Sports Medicine* (2017)	3	49	30.4 (17.2-58.1)	27M/22F	Tunnel widening (>14 mm), suboptimal bone stock, tunnel malposition, failure to secure graft during ACL revision	NR	Chondral defect (12), meniscal tear (6), Chondral defect + meniscal tear (10)	NR	3.1 y (2-5)
Prall et al.[33]	*Injury* (2019)	4	15	29.5	8M/7F	Tunnel widening (>14 mm), extra-anatomically positioned tunnels	NR	NR	Meniscal and chondral lesions treated when indicated	19.8 mo
Theodorides et al.[34]	*Journal of Orthopaedic Surgery* (2019)	4	19	25.2 (16-34)	16M/3F	Tunnel widening (>10 mm), tunnel malposition	Sports twisting injury (12), failure to attend physical therapy (2), poor tunnel placement (2), instability (3)	Meniscal tear (11), chondral damage (4)	NR	3.6 mo (3-11)
Thomas et al.[31]	*American Journal of Sports Medicine* (2005)	3	49	35.4	37M/12F	Tunnel overlap from previous ACLR	NR	Medial compartment cartilage damage (30), Lateral compartment cartilage damage (45)	Medial meniscectomy (42), lateral meniscectomy (26)	6.2y (3-11)

(continued)

Table 1. Continued

Study	Journal (Year)	LOE	No. of Patients	Mean Patient Age (Range), y	Sex (Male/ Female)	Indications for 2-Stage Procedure	Mechanisms (No. of Patients)	Concomitant Injuries (No. of Patients)	Concomitant Procedures (No. of Patients)	Mean Follow-Up (Range)
Uchida et al.[27]	*The Knee* (2016)	4	10	28 (16-43)	6 M/4 F	Tibial tunnel aperture (>20 mm), existing tunnel overlapped with planned tunnels	Sports (5), Other (5)	Meniscus tear (4), cartilage damage (7)	NR	Min. 2 y
Van de Pol et al.[35]	*Arthroscopy* (2018)	4	20	NR	NR	Skeletal maturity, need for 2-stage procedure	NR	NR	NR	52 wk
van Tol et al.[28]	*Journal of Knee Surgery* (2020)	4	42	26.7	24 M/18 F	Tibial tunnel widening (>10-12 mm), incorrect previous tunnel position	NR	Medial meniscus tear (9), lateral meniscus tear (4), meniscal tear developed between first and second stage (4)	Meniscal repair (4), meniscectomy (7),	NR
Ventura et al.[29]	*European Journal of Orthopaedic Surgery and Traumatology* (2014)	4	14	NR	NR	Ahlbäck arthritis score (<3), failure of synthetic graft	NR	NR	NR	4.2 y
von Recum et al.[30]	*Arthroscopy* (2020)	1	37	37. Bone group: 18-48 Si-CaP group: 18-52	Bone group: 14 M/4 F Si-CaP group: 10 M/9 F	Tunnel widening (>10 mm), tunnel confluence	Trauma (18), failure (19)	NR	First stage: partial meniscectomy (7), meniscal repair (3), chondroplasty (2), microfracture (2). Second stage: partial meniscectomy (1), meniscal repair (2), microfracture (1)	Bone group: 64 mo (8-247). Si-CaP group: 75 mo (4-375)

NR, not recorded; MVA, motor vehicle accident; Si-CaP, silicate-substituted calcium phosphate.

overlapping with desired tunnels, or inability to place new tunnels secondary to concern for tunnel confluence.

Surgical Techniques

A total of 12 studies, consisting of 341 patients, underwent bone grafting during the first stage of revision ACLR (Table 2). The most common bone plug used for tunnel grafting during the first stage of revision was iliac crest autograft bone blocks (n = 4 studies, n = 121 patients).[27,30-32] Bone grafting from a graft harvested from the anterior tibial metaphysis was reported in one study (n = 30 patients),[26] whereas 2 studies reported on the use of reamer-irrigated-aspirator harvested bone from the femur (n = 20 patients).[24,33] A synthetic, silicate-substituted calcium phosphate was reported in an experimental group (n = 19 patients) from the single RCT (n = 37 patients).[30] Three studies (82 patients) used allograft bone dowels.[25,28,34] Two studies (69 patients) used allograft bone chips.[16,35] One study (14 patients) did not perform bone grafting during the first stage of revision ACLR.[29] The first stage involved removal of the primary synthetic graft, followed by a 6- to 8-month wait for bone remodeling, and the second-stage revision ACLR.

All studies required a minimum of 3 months between the first- and second-stage procedures (Table 2). The time elapsed between stages was reported by 7 studies, ranging from 21 weeks[28] to 13.6 months.[34]

During the second stage, femoral tunnel drilling was performed using either an anteromedial[16,25,33,35] or transtibial technique,[26,29,30] whereas drilling technique was not reported in 6 studies. ACL graft choice during definitive reconstruction was reported in 12 studies. The use of a hamstring autograft was reported in 9 studies, with both the contralateral hamstring[25,30,32-35] and ipsilateral hamstring[26,30,32] used as graft options. BPTB autograft was used in 8 studies,[16,25,27,29,31-34] and BPTB allograft in 4 studies.[16,27,33,34] van Tol et al.[28] used tibialis anterior/posterior tendon allograft. Graft fixation depended on graft source, consisting of interferences screws, ENDOBUTTON system (Smith & Nephew, London, UK), RIGIDFIX pins (DePuy Synthes, Raynham, MA), and TransFix II device (Arthrex, Naples, FL).

Rehabilitation

Following the first-stage bone grafting procedure, most studies allowed weight-bearing on the operated leg, with some studies allowing for full weight-bearing[25-27,34,35] whereas others allowing for partial weightbearing.[30,32] Rehabilitation after the first-stage procedure consisted of regaining and maintaining full range of motion,[25,30,32,34,35] with reported use of crutches[16,33] and a brace.[27] Following the second-stage ACLR, patients were allowed to weight-bear typically immediately[16,25,26] or within 1 week,[30] with Diermeier et al.[32] only allowing patients to partially weight-bear for the first 2 weeks. Two studies reported patients engaging in full range of motion with no bracing following the second-stage procedure,[25,32] whereas patients in the study from Franceschi et al.[26] were immobilized at a 0° locked brace and von Recum et al.[30] restricted patients to 90° of flexion for the first 10 days. Physical therapy focused on range of motion, edema control, muscle reactivation, muscle strengthening, and proprioceptive training.[16,25,32] Return to sport was typically allowed ranging from 6 months[25,26,30] to 9 months,[16,25] with Franceschi et al.[26] allowing patients to begin running at 3 months.

Imaging Outcomes

Preoperative CT scans were used to assess for tunnel widening in 4 studies, with all 4 studies observing that the preoperative tibial tunnel diameter to be greater than femoral tunnel diameter (Table 3).[24,25,30,33] Coronal-view CT scans were most commonly used to measure the mean femoral tunnel diameter (range 9.7-13.9 mm) and mean tibial tunnel diameter (range 11.7-15.0 mm). Two studies reported on tunnel diameter measurements in the sagittal plane on CT scans, with a greater mean tunnel diameter observed in the sagittal plane (tibial: 13.8 mm, femoral: 11.35 mm) when compared with the coronal view (tibial: 12.8 mm, femoral: 11.36 mm).[25,30] Two studies reported on preoperative tunnel volume. Grote et al.[24] observed a preoperative volume of 7.9 cm^3 and 6.7 cm^3 at the femoral and tibial tunnels, respectively. Meanwhile, Prall et al.[33] reported a mean femoral tunnel volume of 3.8 cm^3 and mean tibial tunnel volume of 6.1 cm^3 preoperatively.

Five studies reported CT scan findings following the first-stage procedure to assess for bony graft integration (Table 3).[24,25,27,33,34] At a mean 121 days after first-stage bone grafting with allograft bone dowels, Buyukdogan et al.[25] found a union ratio (total length of united margin of tibial tunnel divided by tunnel contour, expressed in percentage) and occupying ratio (cross-sectional area of grafted bone divided by cross-sectional area of new tibial tunnel, expressed in percentage) of 83.4 and 85.7, respectively, at the femoral tunnel compared with 74.8 and 87.6, respectively, at the tibial tunnel. Grote et al.[24] and Prall et al.[33] reported better incorporation of the bone graft in the tibial tunnel compared with the femoral tunnel (94% vs 75% and 87.4% vs 76.1%, respectively). Uchida et al.[27] tracked the occupying ratio and bone mineral density over time and found improvements over the course of 3-, 12-, and 24-week follow-ups.

Outcomes from radiographs following the second-stage procedure were reported in 3 studies (Table 3). Prall et al.[33] observed a reduced deviation in femoral

Table 2. Surgical Technique of Included Studies

Study	Years From Primary ACLR (Range)	First-Stage Bone Plug Source	Time Between First and Second Stage (Range)	Second-Stage Graft Source (No. of Patients)	Tibial Fixation	Femoral Fixation	Femoral Tunnel Technique
Buyukdogan et al.[25]	4.3 ± 3.8	Cannulated allograft bone dowel	6.5 mo (2.4-11.5)	Contralateral HT autograft, BPTB autograft	HT: sheath and screw construct BPTB: titanium interference screw	HT: ENDOBUTTON (Smith & Nephew) BPTB: titanium interference screw	Anteromedial portal
Diermeier et al.[32]	NR	Ipsilateral iliac crest	Min. 3 mo	Contralateral hamstring (21), ipsilateral hamstring (12), ipsilateral quadriceps (10), ipsilateral BPTB (1)	Resorbable interference screw	Resorbable interference screw or extra cortical button system	NR
Franceschi et al.[26]	33.8 mo	Safe zone on anterior tibial metaphysis	Min. 3 mo	Ipsilateral Hamstring autograft	Metallic screw (Arthrex)	bioabsorbable screw	Transtibial
Grote et al.[24]	21 mo (11-34)	Reamer–irrigator–aspirator (RIA) harvested bone from femur, Iliac crest (control)	4-5 mo	NR	NR	NR	NR
Mitchell et al.[16]		Opteform allograft bone matrix (Exactech)	Min. 4 mo	BPTB autograft (20), BPTB allograft (29)	Titanium interference screw	Titanium interference screw	Anteromedial portal
Prall et al.[33]		RIA harvested bone from femur	6.2 mo (SD 3.7)	Contralateral hamstring autograft (7), ipsilateral BPTB autograft or quadriceps tendon (4), BPTB allograft (3)	Hamstring: bio-absorbable screw. BPTB: titanium screw	Hamstring: cortical button (ACL TightRope RT). BPTB: titanium screw (Mega-Fix-T)	Anteromedial portal
Theodorides et al.[34]		Allograft bone dowels	13.6 mo (4.5-31)	BPTB auto (10), Hamstring auto (1), BPTB allo (3)	BIOSURE PK Screws (Smith & Nephew)	BPTB: RIGIDFIX pins (DePuy Synthes). Hamstring: ENDOBUTTON	NR
Thomas et al.[31]		Ipsilateral iliac crest	5.8 mo (SD: 1.6 mo)	BPTB (15), 4-strand hamstring (34)	BPTB: Interference screw. Hamstring: Intrafix (Mitek Products)	BPTB: Interference screw. Hamstring: Rigidfix system (Mitek Products)	NR
Uchida et al.[27]	7.6 y (1-20)	Iliac bone block	24-30 weeks	BPTB autograft (8)	NR	NR	NR
Van de Pol et al.[35]		Whole bone allograft sterilized with SCO_2 technique	8.8 mo (5.6-21.3)	Fresh-frozen allograft, live donor, contralateral hamstring	NR	NR	Anteromedial portal
van Tol et al.[28]	1.7 ± 2.1 y	Allograft bone dowels	21 ± 10 wk	Tibialis anterior/posterior tendon allograft	NR	NR	NR
Ventura et al.[29]	9.7 y (5.3-14.4)	No bone grafting	6-8 mo	Hamstring autograft (9), BPTB autograft (5)	BioRCI Interference screw (Smith & Nephew)	Transcondylar pins	Transtibial
von Recum et al.[30]	Bone group: 64 mo (8-247). Si-CaP group: 75 mo (4-375)	Bone group: autologous iliac crest bone Si-CaP group: substituted calcium phosphate	Bone group: 7 mo (5-13) Si-CaP group: 8 mo (5-20)	Ipsilateral hamstring autograft (8), Contralateral hamstring autograft (29)	RetroScrew + suture washer (Arthrex)	TransFix II device (Arthrex)	Transtibial

ACL, anterior cruciate ligament; BPTB, bone–patellar tendon–bone; HT, hamstring; NR, not recorded; SCO_2, supercritical carbon dioxide; SD, standard deviation; Si-CaP, silicate-substituted calcium phosphate; ST, semitendinosus.

Table 3. Imaging and Histologic Outcomes of Included Studies

Study	Preoperative CT	First-Stage Postoperative CT	Second-Stage Postoperative CT	Radiographs
Buyukdogan et al.[25]	Coronal plane, tibia: 14.4 (1.5), femur: 12.9 (1.3). Sagittal plane, tibia: 15.9 (2.2), femur: 12.4 (1.5).	Union ratio (SD), tibia: 74.8 (10.5), femur (83.4 (6.2). Occupying ratio, tibia: 87.6 (4.8), 85.7 (10.1).		
Franceschi et al.[26]	25 grade 0 Fairbanks, 5 grade 1 Fairbanks		19 0 degenerative changes, 7 grade 1 Fairbanks, 4 grade 2 Fairbanks	
Grote et al.[24]	Tunnel: femur: 7.9 cm^3 (SD: 5.3), tibia: 6.7 cm^3 (SD: 5.1)	3-5 mo postoperative: 75% filling femoral tunnel, 94% tibial tunnel		
Prall et al.[33]	Mean femoral tunnel volume: 3.8 cm^3 (SD: 2.7). Mean max femoral diameter: 13.9 mm (SD: 3.3). Mean tibial tunnel volume: 6.1 cm^3 (SD: 2.4). Mean max tibial diameter: 15.0 (SD: 2.9).	4.6 mo postoperative: 76.1% (SD: 12.4) femur, 87.4% (SD: 5.9) tibia. Femoral bone volume: 3.0 cm^3, density 574 HU (SD: 137.5). Tibial bone volume: 5.3 cm^3 (SD: 2.0), density: 516.7 HU (SD: 85.8).		Mean deviation in femoral tunnel apertures: Preoperative: 21.2 ± 9.2% Postoperative: 7.4 ± 3.1%
Theodorides et al.[34]		>75% bone dowel integration (11), Excellent bone dowel integration (5)		
Uchida et al.[27]		Tibia postoperative first stage. Occupying ratio—3 wk: 80.5 ± 4.8, 12 wk: 85.4 ± 4.2, 24 wk: 93.8 ± 3.5. Union ratio—3 wk: 49.1 ± 12.4, 12 wk: 75.2 ± 8.2, 24 wk: 88.5 ± 7.4. Bone mineral density—12 wk: 510 ± 104 mg/cm^3, 24 wk: 572 ± 83 mg/cm^3. Side-to-side BMD ratio—12 wk: 238 ± 91%, 24 wk: 235 ± 94.		
Van de Pol et al.[35]				
Ventura et al.[29]				Postoperative: follow-up: 10 grade 2 osteoarthritis, 2 grade 3, 1 grade 4, 1 grade 5
Von Recum et al.[30]	Bone group—femoral coronal: 11.3 ± 2.3 mm Femoral sagittal: 10.6 ± 2.4 Tibial coronal: 12.1 ± 1.8 Tibial sagittal: 12.6 ± 1.9. Si-CaP group—femoral coronal: 9.7 ± 1.8 Femoral sagittal: 10.9 ± 2.4 Tibial coronal: 11.7 ± 1.3 Tibial sagittal: 12.7 ± 3.2.			Stress radiographs. Bone group laxity preoperative: 8.3 ± 2.2 mm, postoperative: 4.5 ± 2.3. Si-CaP group preoperative: 7.1 ± 3.3 mm, postoperative: 3.9 ± 3.1 mm.

tunnel aperture following two-stage revision ACLR. Ventura et al.[29] reported osteoarthritic changes on radiographic evaluation, with 71% of patients possessing a grade II Ahlback's score after 2-stage revision ACLR. Similarly, Franceschi et al.[26] reported radiographic results at a mean 6.7 years after 2-stage revision ACLR. The authors observed that patients had greater Fairbanks grades compared with the preoperative levels, indicating progressive joint degeneration. Using stress radiographs, von Recum et al.[30] found significant postoperative decreases in knee laxity in both the autologous bone graft and silicate calcium phosphate graft groups at 6-month and final follow-up.

Clinical Outcomes

Patients undergoing 2-stage revision ACLR reported improvement in outcomes across all extracted outcome measures (Table 4). One study reported an improvement in subjective IKDC scores[30] from preoperative to postoperative levels.[29] Four studies showed significant

Table 4. Clinical Outcomes After Two-Stage Revision Anterior Cruciate Ligament Reconstruction

Study	IKDC	Lysholm	Tegner	KT Arthrometer	Lachman	Complications (No. of Patients)
Diermeier et al.[32]	Subjective postoperative: 69.0 ± 13.4	Postoperative: 77.2 ± 15.5	Postoperative: 4.1 ± 1.4	At 30° flexion, postoperative side-to-side difference: 0-2 mm: 79.5% 3-4 mm: 15.4% >5 mm: 5.1%		
Franceschi et al.[26]	Objective preoperative: 18 C, 12 D Postoperative: 27 A and B, 3 C	Preoperative: 65.4 (SD: 7.9, 48-82) Postoperative: 90.2 (SD: 7.9, 72-100)		Preoperative: 7.4 mm Postoperative: 3.1 mm	Preoperative: 19 Grade 2, 11 Grade 3 Postoperative: 24 normal, 6 Grade 1	Hypoesthesia and numbness on tibia (5), joint stiffness (8)
Mitchell et al.[16]		Preoperative: 58 (19-95). Postoperative: 77 (27-100)	Preoperative: 3.5 (1.0-10.0) Postoperative: 5.1 (0-10.0)			
Prall et al.[33]	Objective preoperative: 1 B, 9 C, 2 D. Objective Postoperative: 6 A, 5 B, 1 C, 0 D	Preoperative: 62.5 (SD: 10.5) Postoperative: 85.4 (SD: 7.9).	Preoperative: 2.8 (SD: 0.5) Postoperative: 5.3 (SD: 1.4)			
Theodorides et al.[34]						Pneumonia and PE (1), stitch abscess (1)
Thomas et al.[31]	Subjective postoperative: 61.2 ± 19.6. Objective postoperative: 12 A, 28 B, 8 C, 1 D					
Uchida et al.[27]		Postoperative: 96.6 ± 2.1 (91-100)		At 30° flexion Postoperative: −0.4 ± 1.0 mm (-2-1)	All patients negative postoperative	None
Van de Pol et al.[35]						Reinjury/rupture (1)
Ventura et al.[29]	Objective preoperative: 3 B, 8 C, 3 D. Objective postoperative: 2 B, 9 C, 3 D.			At 20° flexion side-to-side difference Preoperative: 4.8 (SD: 0.8) Postoperative: 4.3 (SD: 1.1)	Preoperative: 6 positive. Postoperative: 4 positive.	Slight extension impairment (2), motion impairment (3), patellofemoral pain (5)
von Recum et al.[30]	Subjective Bone group— Preoperative: 39 ± 10, Postoperative: 64 ± 24. Si-Cap group— Preoperative: 41 ± 18 Postoperative: 64 ± 22.	Bone group— Preoperative: 52 ± 19, Postoperative: 71 ± 21. Si-CaP group— Preoperative: 52 ± 23, Postoperative: 74 ± 22.	Bone group— Preoperative: 2.5 ± 1.1, Postoperative: 4.7 ± 1.9. Si-CaP group— Preoperative: 2.4 ± 2.0, Postoperative: 4.7 ± 1.3.	Postoperative side-to-side Bone group—0.9 ± 1.5 mm Si-CaP group—0.7 ± 2.0 mm.		Insufficient filling (1), iliac crest hematoma (1), infection (1), hemarthrosis (2), cyclops nodule (1)

NOTE. Values are mean ± SD or, range ().
IKDC, International Knee and Documentation Committee; PE, pulmonary embolism; SD, standard deviation; Si-CaP, silicate-substituted calcium phosphate.

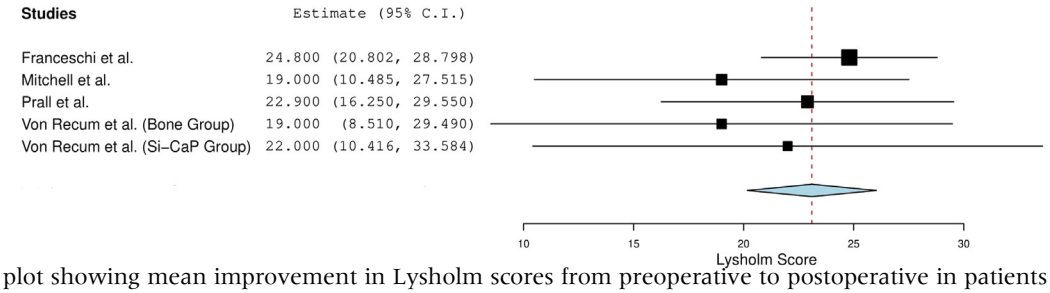

Fig 3. Forest plot showing mean improvement in Lysholm scores from preoperative to postoperative in patients undergoing 2-stage revision anterior cruciate ligament reconstruction. (C.I., confidence interval.)

improvement in Lysholm scores from preoperative to postoperative levels (Fig 3).[16,26,30,33] Similarly, improvements in Tegner scores from preoperative to postoperative levels were identified in 3 studies (Fig 4).[16,30,33] Objective IKDC was improved in 2 studies,[26,33] whereas one study reported no improvement.[29] (Fig 5).[26,29,33] Return to sport outcomes was reported in a single study,[26] in which 66% (n = 20/30) of patients were able to successfully return the original level of sport, with 23% (n = 7/30) returning at a lower activity level and 10% (n = 3/30) unable to return. Complications were reported in 32 patients from 5 studies.[26,29,30,34,35] The most common complications were joint stiffness/movement impairment in 31% (n = 10/32) of patients and hypoesthesia and numbness in 16% (n = 5/32) of patients. There were 5 reported cases of graft failure/re-rupture across three studies.[16,33,35]

Discussion

The most important findings from this study were that (1) tunnel malpositioning and tunnel widening remain the most commonly reported indications for 2-stage revision ACLR, although the threshold for defining significant tunnel widening lacks consensus; (2) there remains considerable variability in the surgical techniques related to bone graft choice, tunnel drilling methods, and graft use during 2-stage revision ACLR; and (3) clinical improvements are generally reported in commonly used patient reported outcomes scores.

Tunnel widening and malposition were the most common indications for 2-stage revision ACLR. However, the precise tunnel diameter threshold warranting a 2-stage reconstruction approach remains controversial, varying based on surgeon preferences and graft choice. Generally, tunnels for hamstring grafts are drilled with a diameter ranging between 7.5 and 9 mm, depending on varying graft diameters and use of quadruple, quintuple or sextuple strand construct, whereas BPTB tunnels are generally drilled using a 10-mm reamer. Studies have used 100% percent tunnel enlargement as an indication for bone grafting in revision ACLR,[36,37] whereas Demyttenaere et al.[38] used a range of 87.5% to 250% tunnel enlargement for bone grafting. Given the variability in tunnel diameter between graft choices, percent tunnel enlargement may serve as a more consistent indication for 2-stage revision surgery than absolute tunnel diameter. Specifically, an Italian expert group consensus recommended that a two-stage approach should be used in cases of tunnel widening greater than 16 mm or with enlargement greater than 100% of the original diameter.[37] Moreover, a 2-stage approach was recommended in cases of infection or severe loss of range of motion.[37] A systematic review by Salem et al.[39] reported inconsistent findings with regard to thresholds for tunnel widening, indicating a 2-stage procedure in the setting of tunnel diameters ranging from 10-15 mm. Further study evaluating outcomes using single and 2-stage reconstruction based on original tunnel size, tunnel widening at the time of injury, as well as the influence of graft choice, are needed to determine the precise tunnel threshold needed for a two-stage procedure as it relates to graft choice and patient characteristics.

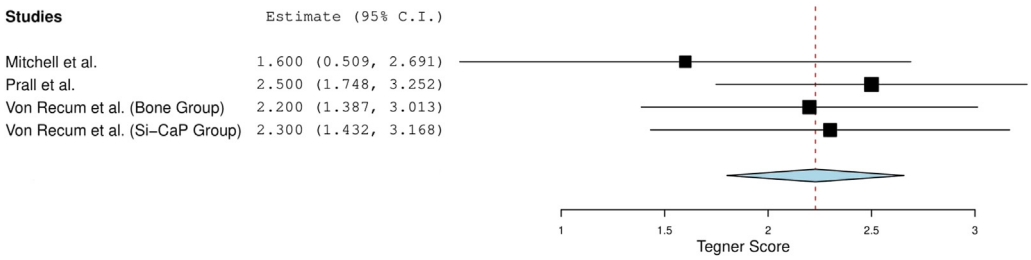

Fig 4. Forest plot showing mean improvement in Tegner scores from preoperative to postoperative in patients undergoing 2-stage revision anterior cruciate ligament reconstruction. (C.I., confidence interval.)

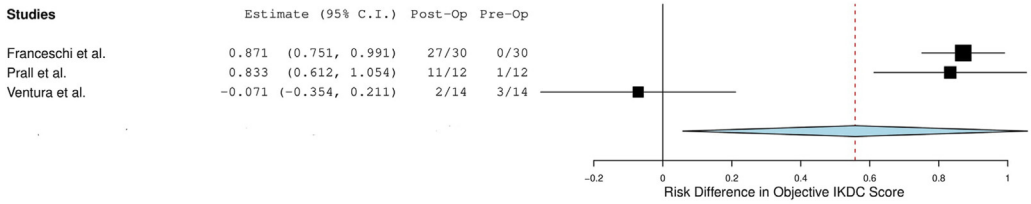

Fig 5. Forest plot of preoperative versus postoperative objective International Knee and Documentation Committee values in patients undergoing 2-stage revision anterior cruciate ligament reconstruction. (C.I., confidence interval.)

Surgical techniques for 2-stage revision ACLR varied across studies. Of note, there was high variability on the choice of bone grafting material during the first-stage procedure. However, in studies reporting bony integration, all the bone plug options were reported on CT scan to successfully integrate. In their systematic-review, Salem et al.[39] analyzed bone-graft options for 2-stage revision ACLR. Based on 5 studies, the authors observed that bone grafting with autografts was associated with lower revision ACLR graft failure. However, several confounding variables could not be controlled for, including sex, age, body-mass index, return to high-risk athletic activity, and graft fixation methods. They also acknowledged limitations in the analysis due to the paucity of literature and lack of high-quality studies comparing bone graft options. Meanwhile, Prall et al.[33] observed comparable filling of bone tunnels when using both cancellous bone autografts and allografts based on CT analysis. Bone graft choice appears to remain primarily at the discretion of the treating surgeon, with further study necessary to determine if one bone graft source yields improved outcomes during 2-stage ACLR.

Historically, the iliac crest or anterior tibial plateau bone autograft has been the gold-standard for first-stage bone grafting.[18] Newer techniques published recently have introduced synthetic and biologically augmented bone grafts.[40,41] Fortier et al.[41] described a technique using allograft bone dowels soaked in bone marrow aspirate concentrate to avoid donor site morbidity. A recent randomized controlled trial comparing results of a synthetic silicate-substituted calcium phosphate to autologous iliac crest bone plugs reported equivalent knee laxity, complications, and clinical outcomes on Tegner, IKDC, Lysholm, and SF-36 scores in both groups.[30] The choice of bone plugs may also explain the variability in time between the two-stages. Although all studies required a minimum of 3 months, there was a broad range of mean time between stages (5.8-13.6 months), perhaps due to different healing times between the bone plugs. The variability found in the technical aspects of the second stage of ACLR as it pertains to graft choice, technique and fixation are consistent with what is observed during primary ACLR.[42] Further research determining the efficacy of these newer techniques, especially as they relate to the use of orthobiologics, is warranted.

Clinical improvements were generally reported when evaluating patient reported outcome measures following 2-stage revision ACLR, with improvements reported in IKDC and Lysholm scores, as well as in the Tegner activity scale relative to preoperative scores. A comparative study by Mitchell et al.[16] observed no difference in clinical outcomes when comparing outcomes in patients undergoing single versus 2-stage approaches, as was the case with the aforementioned metanalysis conducted by Colatruglio et al.[19] which found no major differences in patient-reported outcomes and failure risk between one-stage and staged revision ACLR. Although current literature suggests no difference between 1- and 2-stage revision ACLR, long-term prospective studies are needed to confirm these findings.

The general preference for avoidance of the 2-stage procedure is due the physical and psychological effect on patients having to undergo multiple operations including the extended rehabilitation period, the potential donor-site morbidity, and the additional costs.[25,26] Newer techniques have shown the potential to correct tunnel widening and malposition through a one-stage approach. Tse et al.[43] reported that tunnel filling with bioabsorbable calcium phosphate bone cement is biomechanically viable and could be performed in one-stage procedure. Similarly, Germann et al.[44] incorporated human recombinant bone morphogenic protein-2 with muscle tissue into a semitendinosus graft and observed that it stimulated osseointegration of the graft in oversized bone tunnels in rabbits. Haidar et al.[45] demonstrated that the outside-in technique for femoral tunnel drilling may allow for revision tunnels at different trajectories from the primary tunnels without compromising graft fixation despite tunnel convergence at the inside aperture.

Limitations

This investigation is not without limitations. This review consists of heterogeneous studies, composed of primarily Level III and IV evidence. Furthermore, there was a high level of heterogeneity regarding mean follow-up time, as well as the reported patient-reported

outcome measures. Two-stage revision ACLR is a relatively rare procedure with specific indication, resulting in a relatively small patient population being available for analysis. In addition, as is the case in any systematic review, the search strategy and eligibility criteria may have excluded eligible subgroups of patients or related investigations. Postoperative rehabilitation protocols were infrequently reported, limiting the ability to report any meaningful assessment of commonly reported protocols. Given the limited number of studies, the small number of patients, and the high variability of surgical techniques, it is not possible to make any recommendation regarding optimal timing, bone graft material, graft choice or rehabilitation protocol following two-stage revision ACLR.

Conclusions

Tunnel malpositioning and widening remain the most common indications for 2-stage revision ACLR. Bone grafting is commonly reported using iliac crest autograft and allograft bone chips and dowels, whereas hamstring autograft and BPTB autograft was most used during the second-stage definitive reconstruction. Studies showed improvements from preoperative to postoperative levels in commonly used patient-reported outcomes measures.

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