Systematic Review

Slope-Reducing Proximal Tibial Osteotomy Improves Outcomes in Anterior Cruciate Ligament Reconstruction Patients With Elevated Posterior Tibial Slope, Especially Revisions and Posterior Tibial Slope ≥12

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Purpose: To explore the indications, outcomes, and complications related to slope-reducing osteotomies in the setting of anterior cruciate ligament (ACL) tears or graft failure. A secondary aim was to create an algorithm on the basis of the current literature and authors' opinions. **Methods:** This study was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses. Studies were included if they reported on outcomes related to slope-reducing osteotomies both for primary ACL tears and revision ACL graft tears. The studies were analyzed to determine the radiographic outcomes, patient-reported outcomes (PROs), physical examination findings, and complications. Statistical analysis could not be performed because of the heterogeneity between studies. **Results:** A total of 148 studies were screened for inclusion in this systematic review and after full-text review, a total of 16 studies were included in this systematic review. Fourteen of the studies reported on pre- versus postoperative posterior tibial slope (PTS) and all but one reported significant decrease in PTS. Seven studies reported on pre- versus postoperative PROs, and all studies reported significant improvements in postoperative scores. Anterior tibial translation was measured in 8 studies, and all reported a significant decrease in anterior tibial translation postoperatively. The most common complication was postoperative hyperextension and irritation from hardware. Irritation from hardware was only reported in studies that used plates to fixate the osteotomy. **Conclusions:** In conclusion, slope-reducing proximal tibial osteotomies performed concurrently or as a second-stage surgery with an anterior cruciate ligament reconstruction (ACLR) resulted in improved PROs and decreased ACLR failure rates. Slope-reducing proximal tibial osteotomies are an important treatment consideration for those patients with an increased PTS, especially for patients with a failed ACLR and a PTS ≥12°, to reduce the risk of ACLR failure. **Level of Evidence:** Level IV, systematic review of Level IV studies.

In the setting of an acute anterior cruciate ligament (ACL) tear, the gold standard treatment is anterior cruciate ligament reconstruction (ACLR), especially for younger patients looking to return to high-impact and pivoting activities. However, the failure rates of primary ACLRs are still relatively high, with studies reporting failure rates from 7% to 20%.[1-3] In the setting of a failed ACLR, the patient-specific and technique-based risk factors associated with an ACLR failure should be assessed.[4] Patient-specific risk factors include age, sex, body mass index, hyperlaxity, and coronal and sagittal malalignment, whereas technique-based risk factors include suboptimal reconstruction tunnel placement, graft choice, failure to identify or appropriately treat concomitant injuries, and rehabilitation protocols.[4-6]

One of the more common and increasingly recognized risk factor for ACLR failure is increased posterior tibial slope (PTS), which is commonly described as a PTS ≥12°.[7] Increased PTS has been reported to be an independent risk factor for both an ACL tear and ACLR graft failure as the result of increased graft load.[2,8-11] A study by Salmon et al.[2] reporting on 20-year outcomes

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of ACLR reported a hazard ratio of 3.0 for ACLR hamstring graft rupture for PTS ≥12° compared with PTS <12° for adults and adolescents. In another study, Lee et al.[11] reported PTS ≥12° as a risk factor for ACL graft rupture and reported that for each degree increase of PTS, the risk of ACL graft failure increased 1.37 times. Thus, for patients with increased PTS and an ACLR failure, a slope-reducing osteotomy should be considered to decrease the PTS and, subsequently, the force on the ACL graft.[12]

Although slope-reducing osteotomies are becoming more common, there are still several concerns and differences in techniques. A recent study has highlighted that slope-reducing osteotomies should be corrected to 4° to 6° for an ideal postoperative static anterior tibial translation.[13] Clinical series on slope-reducing proximal tibial osteotomies have reported minimal instances of ACLR graft failure postoperatively at a minimum of 2 years of follow-up[14-16]; however, it is important to recognize that these findings are determined by small case series. In addition, the location at which the proximal tibial osteotomy is made (i.e., supratubercle, transtubercle, and infratubercle) has been reported to result in clinically significantly different outcomes.[17-19] It is challenging to incorporate slope-reducing osteotomies into a primary ACLR with a high PTS when indications remain inconsistent and postoperative protocols often require a more prolonged period of non- or partial weight-bearing.[20] This often leads surgeons to primarily use slope-reducing osteotomies in revision settings.[7] The purpose of this systematic review was to explore the indications, outcomes, and complications related to slope-reducing osteotomies in the setting of ACL tears or graft failure. A secondary aim was to create an algorithm on the basis of the current literature and authors' opinions. We hypothesized that slope-reducing high tibial osteotomy would improve patient-reported outcomes (PROs) in patients with elevated PTS who undergo ACL surgery.

Methods

Article Identification and Selection

This study was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement guidelines and registered on the PROSPERO International prospective register of systematic reviews (CRD42024579450). Searches were performed on PubMed, Embase, Cochrane databases. Article identification was performed in August of 2024. The following search terms were used: slope-reducing osteotomy, anterior closing-wedge proximal (high) tibial osteotomy, posterior opening-wedge proximal (high) tibial osteotomy, high posterior tibial slope, and failure anterior cruciate ligament reconstruction. The search strategy used was as follows:

(((slope reducing osteotomy) OR (slope correcting osteotomy) OR (anterior closing wedge osteotomy) OR (medial opening wedge osteotomy) OR (lateral closing wedge)) AND (ACL) AND ((outcomes) OR (complications) OR (changes)) AND (slope))

All studies from each database were uploaded to EndNote Reference Manager for duplicate article deletion. Two independent investigators (L.V.T. and G.G.) reviewed all abstracts for inclusion criteria. Inclusion criteria consisted of articles which published results on patients.[1] Two reviewers (L.V.T. and M.T.R.) examined all full texts of abstracts meeting the inclusion criteria. Furthermore, all systematic reviews found in the database were examined for additional relevant studies that may have been missed.

Data Collection

Studies were reviewed for data on patient demographics, follow-up times, procedures, fixation methods, indications, and outcomes measures. The main radiographic outcome measures included PTS, patellar height measurements (Caton-Deschamps, Insall-Salvati), and medial proximal tibial angle (MPTA). The main PROs included were the International Knee Documentation Committee (IKDC) scores, Lysholm scores, and Tegner scores. The main physical examination outcomes were anterior tibial translation (ATT) and pivot-shift examination findings. The main complications reported in the studies were ACL failure rates, postoperative hyperextension, and complications, including removal of painful hardware.

Data Analysis

We examined all studies that described the use of slope-reducing, slope-correcting, closing-wedge proximal tibial, or medial-opening slope-correcting or lateral closing slope correcting osteotomies for ACL-deficient knees. After data extraction, Excel (Microsoft Corporation) was used to compile all the data.

Studies in the analysis considered selection bias, small sample sizes, and lack of comparative controls. In many cases, it was not possible to provide controls because of the heterogeneous nature of the enrolled patients across the various studies, ranging from primary ACL tears to multiple revision ACL tears.

Because of significant heterogeneity between the studies and the data reported, a statistical analysis or meta-analysis was not possible. The data were compiled and the means between studies was compared and reported as the ranges of available data. No subgroup analysis was performed, however, comparisons were made between different slope reducing osteotomy techniques and indications and the outcomes.

For the forest plots in the results, the mean pre- and postoperative values were used. The 95% confidence intervals were calculated using the standard deviation

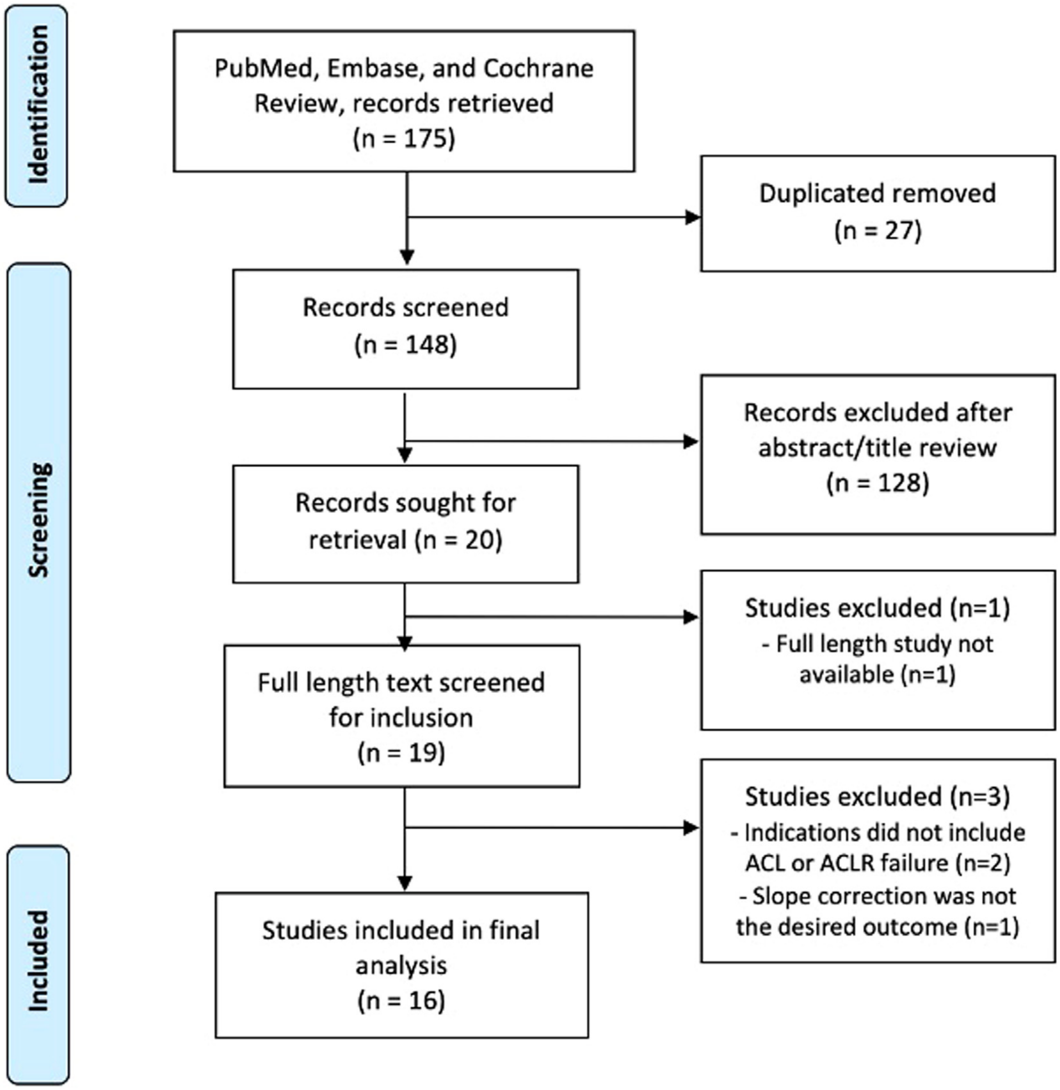

Fig 1. Flowchart for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Sixteen studies were included in the final systematic review. (ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction.)

and was estimated using the range divided by 4 when no standard deviation was reported. No pooling of data or group calculations was performed because of the heterogeneity of the data.

Risk of Bias Assessment

The risk of bias assessment was performed using the Methodological Index for Non-Randomized Studies (MINORS).[21] Nonrandomized noncomparative studies were assessed on a 16-point scale with 8 questions each scored 0 to 2. A score <8 was considered poor quality, 9-13 was considered moderate quality, and 14-16 was considered high quality.

Results

Study Inclusion

A total of 148 studies were identified after the initial search and duplicate removal and 19 full-text studies were reviewed for inclusion. Ultimately, 16 studies were included in the analysis. The flowchart for study inclusion is represented in Figure 1.[13,15,16,18-20,22-31] All studies were graded out of 16 points for the MINORS criteria, the mean score was 9.9 (range, 9-12) (Appendix Table 1, available at www.arthroscopyjournal.org). All studies were considered moderate quality.

Demographic Data

A total of 512 patients were included, and 153 of these were women (29.9%). The mean age range was 21.6 to 36.5 years, and the range of follow-up was 1.5-118.8 months (mean, 29.5 months). All studies included ACL deficiency or ACL or ACLR failure with high PTS as an indication for surgery (Table 1). Most studies used PTS ≥12° (11/16 studies) as the indication for a slope-reducing osteotomy,[13,15,16,18,19,22-27]; however, 1 study reported PTS ≥13° as the indication,[20]

Table 1. Study Summary

Study	Level of Evidence	Patients	Procedure	ACLR	Fixation Method	Indications	Outcome Measures
Akoto et al., 2020[16]	IV	20 (6)	Transtuberosity ACW-PTO	No	Three screws through the tubercle	ACLR failure, high-grade anterolateral laxity, and PTS ≥12°.	PTS, IKDC, Lysholm, Tegner, ATT, pivot-shift
Arun et al., 2016[29]	IV	26 (1)	Medial OWPTO	Yes	Opening-wedge plate	Age ≤40 years, ACL-deficient and varus (grade 2-3 OA)	IKDC, Lysholm
Cance et al., 2024[28]	IV	68 (13)	Supratubercle ACW-PTO	Yes	Two staples	For revision: ACLR failure, anterior laxity, PTS >9°. For primary: ≤20 years, ≥14° PTS, ≥5 mm ATT	PTS, CDI, IS, MPTA
Dan et al., 2024[13]	IV	48 (9)	Supratubercle ACW-PTO	Yes	Two staples	For revision: PTS > 12° and ACL deficiency. For primary: ≤20 years, ≥14° PTS, ≥5 mm ATT	PTS, ATT
Dean et al., 2017[30]	IV	21 (7)	Medial OWPTO	No	Opening-wedge plate	ACLR, meniscus, or extension deficiency.	PTS
Dejour et al., 2015[22]	IV	9 (3)	Supratubercle ACW-PTO	Yes	Two staples	Second revision ACLR, PTS >12°, 2-year follow-up	PTS, CDI, IKDC, Lysholm, ATT, Pivot-Shift, ROM
Guy et al., 2024[23]	IV	47 (15)	Supratubercle ACW-PTO	Yes	Two staples	1+ ACLR and PTS >12°	PTS, CDI, IS
Mabrouk et al., 2023[24]	IV	64 (11)	Supratubercle ACW-PTO	Yes	Medial locked plate or 2 staples.	Third revision ACLR, >12° slope	PTS, IKDC, Lysholm, ATT, pivot-shift, ROM
Mayer et al., 2023[31]	IV	38 (14)	Infratubercle ACW-PTO	Yes (18) No (20)	Anteromedial plate fixation	≥1 previous ACLR	PTS, MPTA, ROM
Onishi et al., 2024[25]	IV	21 (14)	Infratubercle ACW-PTO	Yes	Anteromedial plate fixation	PTS >12°, ACL deficiency	PTS, ROM
Rozinthe et al., 2022[26]	IV	8 (3)	Supratubercle ACW-PTO	Yes	Two staples	Second revision ACLR, PTS >12°, 2-year follow-up	IKDC, Lysholm, pivot-shift, ROM
Song et al., 2020[20]	IV	18 (2)	Infratubercle ACW-PTO	Yes	Anteromedial plate fixation	PTS > 13°, excessive static ATT, and medial meniscus tears.	PTS, Lysholm, Tegner, ATT, pivot-shift, ROM
Sonnery-Cottet et al., 2014[19]	IV	5 (1)	Transtuberosity ACW-PTO	Yes	Screws through tibial tubercle and staples	2 previous ACLRs and PTS >12°	PTS, IKDC, Lysholm, ATT, pivot-shift
Tollefson et al., 2024[27]	IV	20 (14)	Supratubercle ACW-PTO	No	Three staples	≥ 1 ACLR and PTS > 12°	PTS, ATT, CDI
Vivacqua et al., 2023[15]	IV	23 (11)	Supratubercle (19) and transtuberosity (4) ACW-PTO	Yes	Staples or plates	PTS > 12° and previous ACLR failure.	PTS, CDI, IKDC, ATT
Weiler et al., 2022[18]	IV	76 (29)	Infratubercle (48) and supratubercle (10) ACW-PTO, MOW (16) and CW (2) PTO	No	Staples or plates	ACL deficiency, PTS ≥12°	PTS, MPTA

ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; ACW-PTO, anterior closing-wedge proximal tibial osteotomy; ATT, anterior tibial translation; CDI, Caton-Deschamps index; IKDC, International Knee Documentation Committee; IS, Insall-Salvati ratio; MPTA, medial proximal tibial angle; PTO, proximal (high) tibial osteotomy; PTS, posterior tibial slope; ROM, range of motion; OA, osteoarthritis; OWPTO, opening-wedge proximal tibial osteotomy.

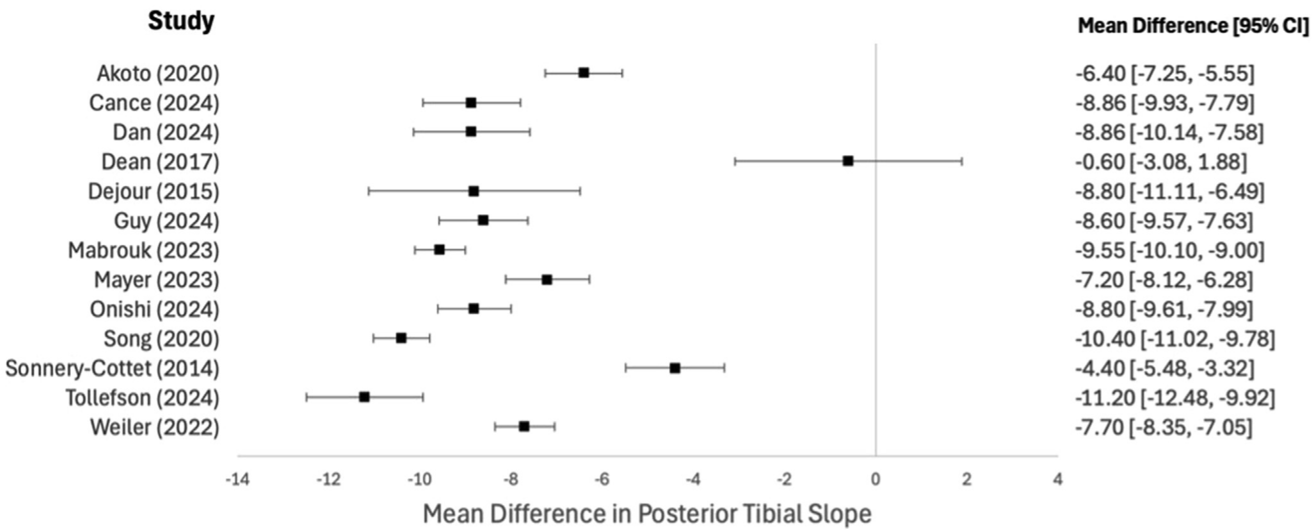

Fig 2. Forest plot of the mean difference in posterior tibial slope for each study that reported mean posterior tibial and the standard deviation for pre- and postoperative values. The study by Vivacqua et al.[15] was not included due to only reporting on interquartile range. (CI, confidence interval.)

1 study reported PTS ≥9° as the indication,[28] and 3 studies did not report on specific PTS values.[29-31] Some studies used various osteotomy techniques; however, supratubercle anterior closing-wedge proximal tibial osteotomy (ACW-PTO) was the most common technique (9/16),[13,15,18,22-24,26-28] followed by infratubercle ACW-PTO (4/16),[18,20,25,31] transtuberosity ACW-PTO (3/16),[15,16,19] medial OW-PTO (3/16),[18,29,30] and medial CW-PTO (1/16).[18]

Radiographic Outcomes

Fourteen studies reported on PTS values, with all but one reporting a significant decrease ($P < .05$) in the mean PTS from a range of 10.1° to 18.5° preoperatively to 3.6° to 9.5° postoperatively (Δ range = 0.6° to 11.2°).[13,15,16,18-20,22-25,27,28,30,31] The one study that did not report a significant difference used a posteromedial opening-wedge plate and an anterior staple.[30] Ten of the 14 studies reported on using the medial tibial plateau and the anatomic axis of the tibia for the PTS measurements.[13,16,18-20,22,25,28,30,31] Five studies reported on the Caton-Deschamps Index,[15,22,23,27,28] and 2 studies reported on the Insall-Salvati Index (ISI).[23,28] For the mean Caton-Deschamps Index, the preoperative ratio ranged from 0.93 to 1.03, and the postoperative ratio ranged from 0.90 to 1.10 (Δ range = −0.07 to 0.09). Two studies reported no significant difference between pre- and postoperative values,[23,27] 2 studies reported significantly increased patellar height after surgery,[15,28] and 1 study did not report statistical findings.[22] There was no significant difference between the mean preoperative ISI ratio (1.71 and 1.0) and postoperative ISI ratio (1.73 and 0.9) values for the ISI in the studies reporting these values.[23,28] Three studies reported on the mean MPTA, with a preoperative MPTA range of 86.16° to 87.3° and a postoperative MPTA range of 85.2° to 86.2° (Δ range = −1.13 to −0.9°).[18,28,31] Two of those studies reported a significantly decreased MPTA after a slope-reducing surgery, suggesting a shift into varus of the tibia in the coronal plane.[28,31] Results are summarized in Figure 2 and Table 2.

Patient-Reported Outcomes

Eight studies reported on PROs, with a range of mean follow-up of 26.7 to 118.8 months (mean, 49.9 months).[15,16,19,20,22,24,26] Six studies reported on the mean IKDC with a preoperative range of 38.0 to 44.1 and a postoperative range of 52.4 to 87.4 (Δ range = 27.5 to 39.6).[15,16,19,22,24,26] The 3 studies that reported on pre- and postoperative values reported significant increases in IKDC from pre- to postoperatively.[19,22,24] Six studies reported on the mean Lysholm scores with a preoperative range of 38.4 to 51.94 to a postoperative range of 73.8 to 90.9 (Δ range = 22.51 to 43).[16,19,20,22,24,26] The 5 studies that reported on pre- and postoperative values all reported significant increases in Lysholm scores.[16,19,20,22,24] Two studies reported on the mean Tegner activity scale, and both reported significant increases from an mean preoperative value of 2.9 and 5.7 to a mean postoperative value of 6.1 and 7.3, respectively.[16,20] One study, by Arun et al.,[29] did not report on specific PTS values, but rather compared those with PTS corrections of >5° and <5° and reported that those with a correction of >5° reported significantly greater increases in IKDC and Lysholm (increases of 19.86 and 27.14, respectively) scores compared with the <5° slope correction cohort

Table 2. Radiographic Outcomes

Study	PTS, °			CDI (Ratio)		ISI (Ratio)		MPTA, °	
	Preop	Postop	Measurement Technique	Preop	Postop	Preop	Postop	Preop	Postop
Akoto et al., 2020[16]	15.3	8.9*	Medial tibial plateau						
Cance et al., 2024[28]	12.5	3.6*	Medial tibial plateau	0.93	1.01*	1.71	1.73	86.2	85.2*
Dan et al., 2024[13]	12.5	3.6*	Medial tibial plateau						
Dean et al., 2017[30]	10.1	9.5	Medial tibial plateau						
Dejour et al., 2015[22]	13.2	4.4*	Medial tibial plateau	0.97	0.9*				
Guy et al., 2024[23]	14.7	6.1*	Mean of both plateaus	1	1	1	0.9		
Mabrouk et al., 2023[24]	13.8	4.2*	Lateral tibial plateau						
Mayer et al., 2023[31]	14.6	7.4*	Medial tibial plateau					86.5	85.2*
Onishi et al., 2024[25]	14.5	5.7*	Medial tibial plateau						
Song et al., 2020[20]	18.5	8.1*	Medial tibial plateau						
Sonnery-Cottet et al., 2014[19]	13.6	9.2*	Medial tibial plateau						
Tollefson et al., 2024[27]	15.2	4*	Lateral tibial plateau	1.03	1.07				
Vivacqua et al., 2023[15]	14	4*	NA	1.01	1.1*				
Weiler et al., 2022[18]	14.5	6.8*	Medial tibial plateau					87.3	86.2

NOTE. Posterior tibial slope (PTS) was recorded for preoperative (preop) and postoperative (postop) in 14 of the 16 studies. The method of measuring posterior tibial slope was also included. Patellar height measurements including the Caton-Deschamps Index (CDI) and Insall-Salvati Index (ISI) were also included. The medial proximal tibial angle (MPTA) was also included to report coronal plane changed.

NA, not available.

*Statistically significant difference from preoperative values ($P \geq .05$).

(increases of 10.67 and 10.33, respectively). Results are summarized in Figure 3 and Table 3.

Physical Examination

Eight studies reported on pre- and postoperative ATT values using a combination of a Rolimeter,[16] Telos device,[19,22] GNRB arthrometer,[24] KT-1000 arthrometer,[20] and radiographs.[13,15,27] The mean preoperative ATT ranged from 5.38 mm to 16.6 mm and the mean postoperative ATT ranged from −2.55 mm to 7.7 mm (Δ range = −11.5 mm to −4.03 mm).[13,15,16,19,20,22,24,27] All 8 studies reported significant decreases in ATT from pre- to postoperative, regardless of whether the ACLR was performed at the same time as the osteotomy or in a staged fashion.[13,15,16,19,20,22,24,27] Four studies reported on the pre- and postoperative pivot-shift tests.[16,19,20,24] One study reported a grade 3 pivot-shift test for all preoperative cases and grade 0 for all postoperative cases.[16] One study reported 15 grade 2 pivot shifts and 3 grade 3 pivot-shift tests preoperatively and grade 0 pivot-shift tests for all postoperative cases.[20] One study reported 1 grade 1, 3 grade 2, and 1 grade 3 pivot-shift tests

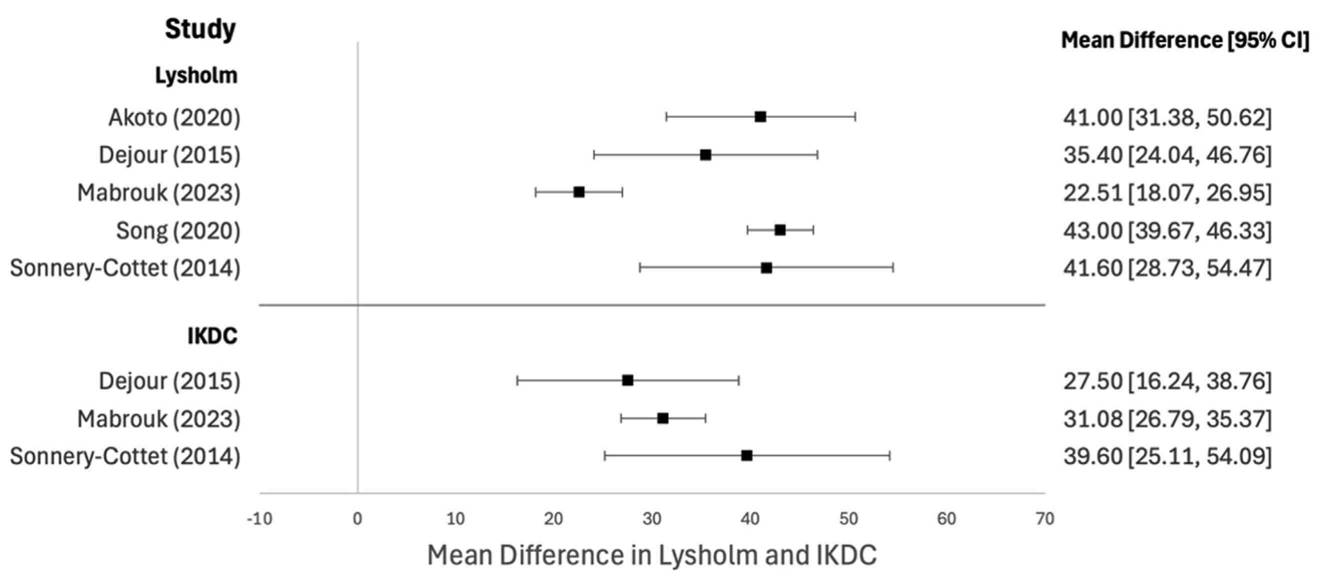

Fig 3. Forest plot of the mean difference in IKDC and Lysholm scores for each study that reported mean Lysholm or IKDC scores and the standard deviation for pre- and postoperative values. When only range was provided, the standard deviation was estimated as a quarter of the range. (CI, confidence interval; IKDC, International Knee Documentation Committee.)

Table 3. Patient-Reported Outcomes

Study	Lysholm		IKDC		Tegner	
	Preop	Postop	Preop	Postop	Preop	Postop
Akoto et al., 2020[16]	49.9	90.9*		87.4	2.9	6.1*
Dejour et al., 2015[22]	38.4	73.8*	44.1	71.6*		
Mabrouk et al., 2023[24]	51.9	74.5*	38	69.1*		
Rozinthe et al., 2022[26]		84.5		82.9		
Song et al., 2020[20]	46.5	89.5*			5.7	7.3*
Sonnery-Cottet et al., 2014[19]	46.2	87.8*	39.5	79.1*		
Vivacqua et al., 2023[15]				52.4		

Lysholm, International Knee Documentation Committee (IKDC), and Tegner scores are included from the 7 studies that reported these patient-reported outcomes (PROs) scores.

Preop, preoperative; postop, postoperative.

*Statistically significant difference from preoperative values ($P \geq .05$).

preoperatively and 4 grade 0 and 1 grade 1 pivot-shift tests postoperatively.[19] The final study reported significant heterogeneity with 15 grade 0, 17 grade 1, 22 grade 2, and 10 grade 3 pivot-shift tests preoperatively and 22 grade 0, 25 grade 1, 14 grade 2, and 3 grade 3 pivot-shift tests postoperatively.[24] Results are summarized in Figure 4 and Table 4.

Failures and Complications

Only 2 studies reported failures, which were classified as graft failures and/or clinical insufficiency. One study had 3 of 64 failures (4.7%) of which were all ACL graft failures.[24] Another study had 3 of 23 failures (13.0%) citing ACLR graft failure for 2 patients and persistent graft instability for 1 patient.[15] A postoperative increase in hyperextension was reported in 5 studies, with 2 studies reporting an mean increase of 2.58° and 2.9° of recurvatum postoperatively.[24,25] One study was a continuation of another study, which reported increased hyperextension of >5° in 2 of 9 patients at the initial 2-8 years follow-up and increased hyperextension of >5° in 2 of 8 patients at 7-15 years follow-up.[22,26] One other study reported an increase in hyperextension of >5° in 8 of 18 patients.[20] Complications varied between studies. Symptomatic hardware was reported in 4 studies,[15,24,30,31] changes in patellar height were reported in 2 studies,[23,25] progression of osteoarthritis was reported in 3 studies,[19,22,26] and other complications (infection/hematoma/embolism) was reported in 3 studies.[16,30,31] For the 4 studies that reported hardware irritation, the percent of patients who had hardware removal ranged from 17.2% to 26.1%.[15,24,30,31] Two of the studies used posteromedial plates and 2 of the studies included both plate fixation

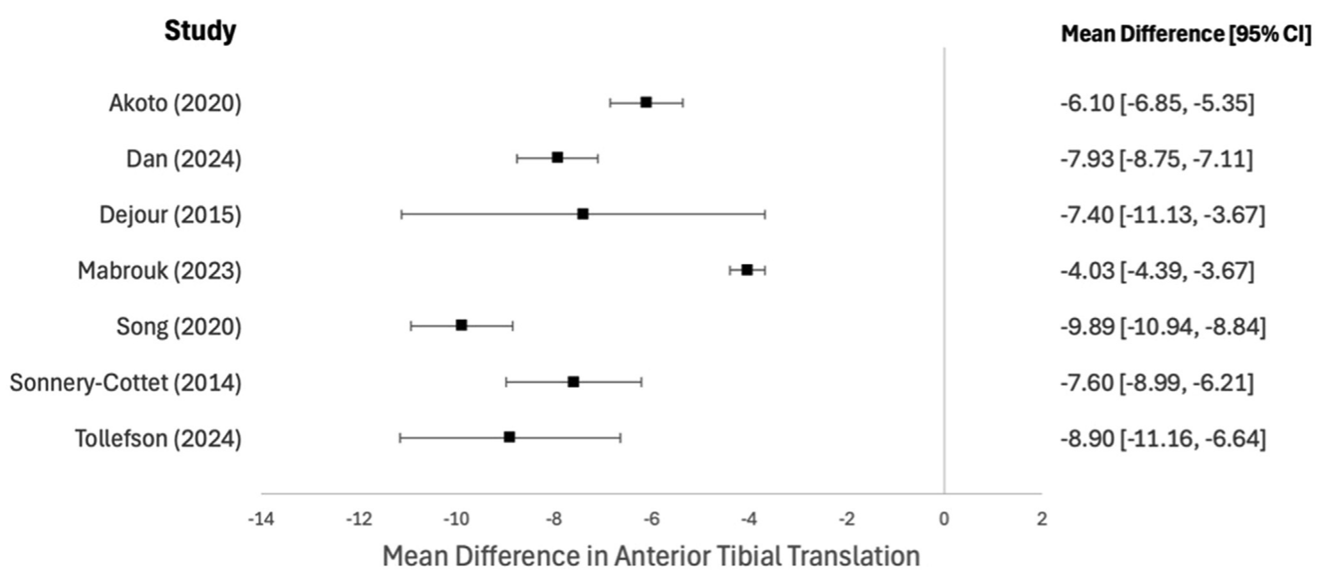

Fig 4. Forest plot of the mean difference in anterior tibial translation for each study that reported mean anterior tibial translation and the standard deviation for pre- and postoperative values. When only range was provided, the standard deviation was estimated as a quarter of the range. The study by Vivacqua et al.[15] was not included because they only included the interquartile range. (CI, confidence interval.)

Table 4. Physical Examination Outcomes

Study	ATT, mm			Pivot Shift Test (Grade)		Postop ROM, °
	Preop	Postop	Device Used	Preop	Postop	
Akoto et al., 2020[16]	7.2	1.1*	Rolimeter	3 = 20	0 = 20	
Dan et al., 2024[13]	5.4	-2.6*	Lateral radiographs			
Dejour et al., 2015[22]	11.7	4.3*	Telos		0 = 8, 1 = 1	2 with ≥5° hyperextension
Mabrouk et al., 2023[24]	7	2.9*	GNRB Arthometer	0 = 15, 1 = 17, 2 = 22, 3 = 10	0 = 22, 1 = 25, 2 = 14, 3 = 3	2.58° increase in recurvatum
Onishi et al., 2024[25]						2.9° increase in recurvatum
Rozinthe et al., 2022[26]					0 = 8	1 with ≥10°, 2 with ≥5° hyperextension
Song et al., 2020[20]	11.1	1.2*	KT-1000	2 = 15, 3 = 3	0 = 18	8 with ≥5° hyperextension
Sonnery-Cottet et al., 2014[19]	10.4	2.8*	Telos	1 = 1, 2 = 3, 3 = 1	0 = 4, 1 = 1	
Tollefson et al., 2024[27]	16.6	7.7*	Lateral radiographs			
Vivacqua et al., 2023[15]	8.5	3.6*	Lateral radiographs			

NOTE. The anterior tibial translation (ATT) was recorded in millimeters, and the device used to measure ATT was also included The grade of pivot shift tests and range of motion 23measurements were also included.
ROM, range of motion.
*Statistically significant difference from preoperative values ($P \geq .05$).

and staple fixation,[15,24] but did not differentiate which patients had their hardware removed. No studies with just staple fixation reported any hardware irritation. It is important to note that Song et al.[20] used anteromedial plate fixation and did not specifically report hardware irritation, but they removed the hardware in all patients. All studies that reported on exclusively staple fixation did not report hardware irritation or specifically report on hardware removal.

Discussion

The most important finding from this systematic review was that nearly all studies that used a slope-reducing osteotomy technique reported a significant decrease in PTS and ATT from pre- to postoperative values. In addition, PROs, including IKDC, Lysholm, and Tegner scores, were significantly increased from pre- to postoperative values for an ACLR performed concurrently or in a second stage after a slope-reducing proximal tibial osteotomy. Furthermore, although ACLR failure rates after slope-reducing PTO were low across studies, complications including symptomatic hardware and increased recurvatum postoperatively after a slope-reducing osteotomy were reported. Symptomatic hardware removal was only reported in studies that used plate fixation rather than just staple fixation.

This study reported that in most cases, a slope-reducing osteotomy led to significantly decreased PTS and ATT compared with preoperative values. Slope-reducing osteotomies performed in the setting of an ACL tear or ACL graft failure with high PTS are used to decrease the force on the ACLR graft by minimizing the amount of ATT. Previous biomechanical and clinical studies have both highlighted the important correlation between PTS, ATT, and ACL graft forces and failure rates. In their biomechanical study, Bernhardson et al.[12] reported that the mean force on the ACL graft increased linearly as slope increased. This increased force has been postulated to lead to fatigue failure of ACLR grafts. Clinical studies by Salmon et al.[2] and Lee et al.[11] both reported that patients with a PTS ≥12° have a significantly increased risk of ACL graft failure, and failure rates continued to increase as slope increased. Studies by Cance et al.[32] and Dejour and Bonnin[33] have reported significant increases in ATT of the ACL injured knee compared with the normal knee with tibial slopes ≥12° when measured via lateral weight-bearing radiographs. The study by Cance et al.[28] also correlated increases in posterior tibial slope to increases in ATT. As slope increased, the force experienced by the ACL or ACL graft increased, and this increased force also caused an increase in ATT. The studies included in this systematic review follow much of the current literature reporting that a posterior tibial slope ≥12° as the indication for a slope-reducing osteotomy in 11 of 16 (68.8%) studies. These findings, together with previous studies, suggest that patients in the revision ACLR setting with a PTS ≥12° should be evaluated to undergo a slope-reducing osteotomy to reduce the risk of ACLR graft failure.

In this systematic review, every study which analyzed pre- and postoperative values for the IKDC, Lysholm, and Tegner scores, reported significant increases from pre- to postoperative values. Across the studies that reported on these outcomes, significant and minimally clinically important differences (MCID) were reported across all outcomes from preoperative to postoperative values. The MCID for IDKC is 16.7, the MCID for Lysholm is 8.9, and the MCID for Tegner is 1.[34] The study with the longest follow-up was by Rozinthe et al.,[26] which reported on 8 patients with a slope-reducing proximal tibial osteotomy and concomitant re-revision ACLR with an mean follow-up of 9.9 years. This series was a longer-term follow-up on the original series by Dejour et al.[22] in 2015. They reported an increased IKDC score of 82.9 compared with an IKDC score of 71.6 at 4.0 years postoperatively (the preoperative IKDC score from the original study by Dejour et al.[22] was 44.1), minimal progression of osteoarthritis, and no meniscal or re-revision ACLR graft tears. The study by Akoto et al.[16] reported on 20 patients who underwent a 2-stage surgery for both primary and revision ACLR patients with a mean 30.5-month follow-up, and reported a final IKDC score of 87.4, a Lysholm score improvement from 49.9 to 90.9, Tegner score improvement from 2.9 to 6.1, and no ACLR failures. Overall, these studies, along with the others presented in this systematic review, report improved postoperative outcomes for both primary and revision ACLR for patients undergoing slope-reducing osteotomies.

Complications and failures were relatively low across the studies in this systematic review, but a few trends could be observed. In the 2 studies that performed ACLR and slope-reducing osteotomies and reported failures, ACLR failure rates were 4.7%[24] and 13.0%.[15] The rest of the studies did not report ACLR failure at their respective follow-up periods. These findings suggest that slope-reducing osteotomies with ACLR are effective in reducing ACLR graft failure. A few of the complications associated with a slope-reducing osteotomy are a risk of postoperative hyperextension and irritation from hardware. Because of the requirement for a decreased tibial slope, there is a risk of iatrogenic genu recurvatum postoperatively as the tibial slope is flattened.[35,36] Although it has not been well defined as to when genu recurvatum becomes symptomatic and reduces function, it was noted in the study by Song et al.[20] that 8 of 18 patients had "mild hyperextension" of 5°. Akoto et al.[16] reported that 3/20 patients had genu recurvatum postoperatively and all were reported to be asymptomatic. Rozinthe et al.[26] reported hyperextension of 5° and 10° in 2 of their 8 patients. To address painful hardware, a hardware removal occurred in 29 of 512 (5.7%) of patients in this systematic review. Only studies reporting the use of plate fixation reporting symptomatic hardware. In addition, Song et al.[20] reported fixation with a plate and screws (TomoFix; Synthes) and all osteotomy hardware was removed postoperatively; however, they did not report specifically whether there was hardware irritation. These complications suggest that staple fixation may be optimal to avoid hardware irritation and that postoperative hyperextension in the rehabilitation phase after a slope correcting osteotomy should be avoided in the initial 2 to 3 months to limit potential postoperative recurvatum.

Authors' Preferred Treatment Algorithm

The initial workup for a patient with a suspected ACL tear should include a thorough history, physical examination, and imaging. Radiographs and MRI should be obtained to assess coronal and sagittal plane alignment and confirm the presence of an ACL tear. It is well recognized that the measurement of PTS has not been standardized across studies, with slope measurements being reported off MRI scans, short lateral radiographs, and long tibial lateral alignment radiographs. In addition, measurements of the medial tibial slope, lateral tibial slope, and the mean slope have been reported among studies, which makes comparisons among studies problematic. On the basis of biomechanical, clinical, and radiographic data, the present authors' preferred technique is to report on PTS measurement using a long lateral tibial alignment radiograph and measuring the anatomic axis off the lateral tibial plateau.[37] In addition, optimal radiographs should have the posterior margins of the medial and lateral femoral condyles overlapping and the fibula overlapping the tibia by one-third because it has been reported that axial rotation of the tibia by 15° tends to decrease PTS by 1° to 2°.[38] The flowchart in Figure 5 shows the authors' preferred treatment algorithm.

Because of the convincing evidence of an increased PTS on ACLR success rates, the PTS should be calculated for all patients with a primary or revision ACL tear. For a primary ACLR with a PTS <12°, an ACLR with a patellar tendon autograft is our preferred treatment. For primary ACLR with a PTS between 12° and 18°, a patellar tendon autograft concurrent with an anterolateral complex surgery (either an anterolateral ligament reconstruction or a lateral extra-articular tenodesis), is recommended. For a primary ACLR with a PTS ≥18°, consideration for solely an ACLR with a lateral extra-articular tenodesis (LET) or a combined slope-reducing proximal tibial osteotomy and an ALCR and LET can be considered in patients with closed physes. For patients with significantly increased ATT

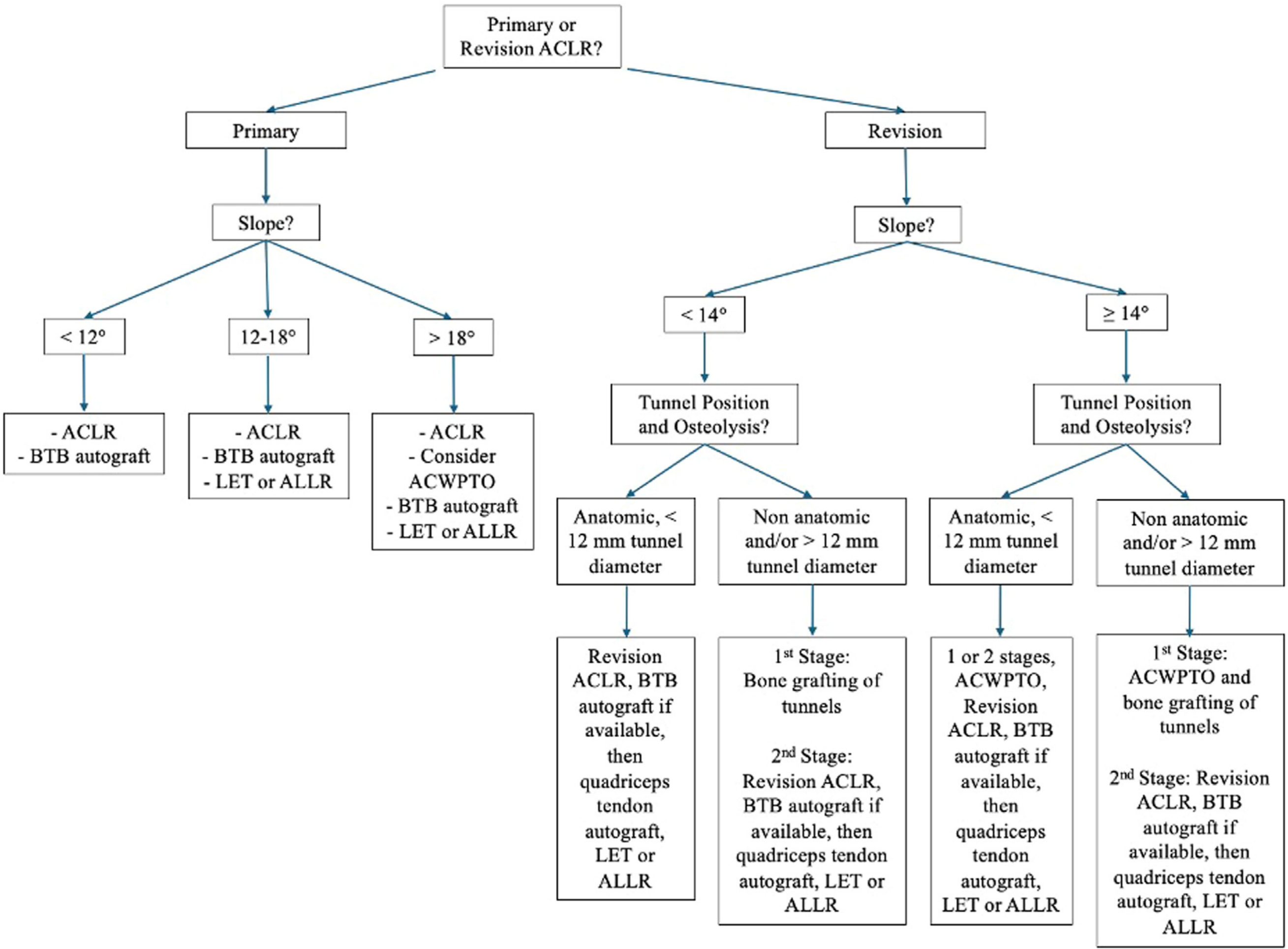

Fig 5. Flowchart depicting the authors preferred treatment algorithm for a patient with an anterior cruciate ligament (ACL) tear or ACL graft tear. Posterior tibial slope (PTS) should be assessed in both the primary and revision setting. In the revision setting, tunnel osteolysis via a computed tomography scan should be performed and tunnel diameter should be measured. Typical treatment algorithms should favor the use of a bone−patellar tendon−bone (BTB) or quadriceps tendon autograft with a (LET) or anterolateral ligament reconstruction (ALLR) in high slope settings. In revision cases, a slope correcting osteotomy should be considered for PTS ≥14°. Bone grafting should be considered when tunnel diameter is ≥12 mm. (ACLR, anterior cruciate ligament reconstruction.)

(>10 mm) and a PTS ≥18°, a slope-reducing osteotomy in the primary phase may be indicated.

It is important for the workup of revision ACLRs to carefully assess for the etiology of the original ACLR failure. For patients with a failed ACLR, it is important to first verify the sizes and positions of the failed ACLR tunnels via computed tomography scans. If the PTS is <14° and the ACLR tunnels are <14 mm in diameter and are in anatomic position, a single-stage revision ACLR with LET or ALL can be performed, preferable with bone−patellar tendon−bone or quadriceps tendon with bone plug grafts. If the PTS is <14° and the ACLR tunnels are ≥14 mm or are malpositioned, a planned 2-stage tunnel bone grafting, followed by a revision ACLR with LET or anterolateral ligament reconstruction at approximately 6 months postoperatively once the bone grafted tunnels have healed, is recommended. If the PTS is ≥14° and the ACLR tunnels are ≥14 mm or are malpositioned, a planned 2-stage slope-reducing osteotomy with tunnel bone grafting, followed by a revision ACLR with LET or anterolateral ligament reconstruction at approximately 6 months postoperatively once the bone grafted tunnels and slope-reducing osteotomy have healed, is recommended. For patients with a failed ACLR and a PTS ≥14° and previous ACL tunnels that are not dilated or non-anatomically positioned, a one-stage revision ACLR and LET procedure concurrent with a slope-reducing osteotomy is recommended.

Limitations

The authors recognize some limitations with this systematic review. First, many of the studies were Level IV studies with low numbers of patients. Second, PROs were reportedly differently among the studies, so direct comparisons were difficult. In addition, because of significant heterogeneity between the studies and the reported outcomes, a statistical analysis or pooling between the studies was not possible. For example, the measurements for ATT used 5 different techniques across the 8 studies. Furthermore, all studies included in this systematic review were of moderate quality according to the MINORS criteria. More high-quality studies related to slope-reducing osteotomies are required in the future for better analysis and potential meta-analysis in the future. Finally, the complications among the various studies were not well defined, with many studies not specifically reporting whether they had complication or ACL failures.

Conclusions

In conclusion, slope-reducing proximal tibial osteotomies performed concurrently or as a second-stage surgery with an ACLR resulted in improved PROs and decreased ACLR failure rates. Slope-reducing proximal tibial osteotomies are an important treatment consideration for those patients with an increased PTS, especially for patients with a failed ACLR and a PTS $\geq 12°$ to reduce the risk of ACLR failure.

Disclosures

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References

1. Barber-Westin S, Noyes FR. One in 5 athletes sustain reinjury upon return to high-risk sports after ACL reconstruction: A systematic review in 1239 athletes younger than 20 years. *Sports Health* 2020;12:587-597.
2. Salmon LJ, Heath E, Akrawi H, Roe JP, Linklater J, Pinczewski LA. 20-year outcomes of anterior cruciate ligament reconstruction with hamstring tendon autograft: The catastrophic effect of age and posterior tibial slope. *Am J Sports Med* 2018;46:531-543.
3. Rezansoff A, Firth AD, Bryant DM, et al. Anterior cruciate ligament reconstruction plus lateral extra-articular tenodesis has a similar return-to-sport rate to anterior cruciate ligament reconstruction alone but a lower failure rate. *Arthroscopy* 2024;40:384-396.e381.
4. Ziegler CG, DePhillipo NN, Kennedy MI, Dekker TJ, Dornan GJ, LaPrade RF. Beighton score, tibial slope, tibial subluxation, quadriceps circumference difference, and family history are risk factors for anterior cruciate ligament graft failure: A retrospective comparison of primary and revision anterior cruciate ligament reconstructions. *Arthroscopy* 2021;37:195-205.
5. Roethke LC, Braaten JA, Rodriguez AN, LaPrade RF. Revision anterior cruciate ligament reconstruction (ACLR): Causes and how to minimize primary ACLR failure. *Arch Bone Joint Surg* 2023;11:80-93.
6. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. Meniscal tears, posterolateral and posteromedial corner injuries, increased coronal plane, and increased sagittal plane tibial slope all influence anterior cruciate ligament-related knee kinematics and increase forces on the native and reconstructed anterior cruciate ligament: A systematic review of cadaveric studies. *Arthroscopy* 2022;38:1664-1688.e1661.
7. Duerr R, Ormseth B, Adelstein J, et al. Elevated posterior tibial slope is associated with anterior cruciate ligament reconstruction failures: A systematic review and meta-analysis. *Arthroscopy* 2023;39:1299-1309.e1296.
8. Cruz CA, Mannino BJ, Pike A, et al. Increased posterior tibial slope is an independent risk factor of anterior cruciate ligament reconstruction graft rupture irrespective of graft choice. *J ISAKOS* 2022;7:100-104.
9. Dean RS, DePhillipo NN, LaPrade RF. Posterior tibial slope in patients with torn ACL reconstruction grafts compared with primary tear or native ACL: A systematic review and meta-analysis. *Orthop J Sports Med* 2022;10:23259671221079380.
10. Duerr RA, Ormseth B, DiBartola A, et al. Association of elevated posterior tibial slope with revision anterior cruciate ligament graft failure in a matched cohort analysis. *Am J Sports Med* 2023;51:38-48.
11. Lee CC, Youm YS, Cho SD, et al. Does posterior tibial slope affect graft rupture following anterior cruciate ligament reconstruction? *Arthroscopy* 2018;34:2152-2155.
12. Bernhardson AS, Aman ZS, Dornan GJ, et al. Tibial slope and its effect on force in anterior cruciate ligament grafts: Anterior cruciate ligament force increases linearly as posterior tibial slope increases. *Am J Sports Med* 2019;47:296-302.
13. Dan MJ, Cance N, Pineda T, Demey G, Dejour DH. Four to 6 degrees is the target posterior tibial slope after tibial deflection osteotomy according to the knee static anterior tibial translation. *Arthroscopy* 2024;40:846-854.
14. Dejour D, Rozinthe A, Demey G. ReSurg. First revision ACL reconstruction combined with tibial deflexion osteotomy improves clinical scores at 2 to 7 years follow-up. *Knee Surg Sports Traumatol Arthrosc* 2023;31:4467-4473.
15. Vivacqua T, Thomassen S, Winkler PW, et al. Closing-wedge posterior tibial slope-reducing osteotomy in complex revision ACL reconstruction. *Orthop J Sports Med* 2023;11:23259671221144786.

16. Akoto R, Alm L, Drenck TC, Frings J, Krause M, Frosch KH. Slope-correction osteotomy with lateral extra-articular tenodesis and revision anterior cruciate ligament reconstruction is highly effective in treating high-grade anterior knee laxity. *Am J Sports Med* 2020;48:3478-3485.
17. Servant C. Editorial Commentary: Different levels for posterior tibial slope reducing anterior closing wedge osteotomy to reduce anterior cruciate ligament reconstruction failure present different risks. *Arthroscopy* 2024;40:1555-1556.
18. Weiler A, Gwinner C, Wagner M, Ferner F, Strobel MJ, Dickschas J. Significant slope reduction in ACL deficiency can be achieved both by anterior closing-wedge and medial open-wedge high tibial osteotomies: Early experiences in 76 cases. *Knee Surg Sports Traumatol Arthrosc* 2022;30:1967-1975.
19. Sonnery-Cottet B, Mogos S, Thaunat M, et al. Proximal tibial anterior closing wedge osteotomy in repeat revision of anterior cruciate ligament reconstruction. *Am J Sports Med* 2014;42:1873-1880.
20. Song GY, Ni QK, Zheng T, Zhang ZJ, Feng H, Zhang H. Slope-reducing tibial osteotomy combined with primary anterior cruciate ligament reconstruction produces improved knee stability in patients with steep posterior tibial slope, excessive anterior tibial subluxation in extension, and chronic meniscal posterior horn tears. *Am J Sports Med* 2020;48:3486-3494.
21. Slim K, Nini E, Forestier D, Kwiatkowski F, Panis Y, Chipponi J. Methodological index for non-randomized studies (minors): Development and validation of a new instrument. *ANZ J Surg* 2003;73:712-716.
22. Dejour D, Saffarini M, Demey G, Baverel L. Tibial slope correction combined with second revision ACL produces good knee stability and prevents graft rupture. *Knee Surg Sports Traumatol Arthrosc* 2015;23:2846-2852.
23. Guy S, Saithna A, Ferreira A, et al. The influence of tibial tubercle-sparing slope-reducing osteotomy on patellar height in patients undergoing revision ACL reconstruction. *Am J Sports Med* 2024;52:919-927.
24. Mabrouk A, Kley K, Jacquet C, Fayard JM, An JS, Ollivier M. Outcomes of slope-reducing proximal tibial osteotomy combined with a third anterior cruciate ligament reconstruction procedure with a focus on return to impact sports. *Am J Sports Med* 2023;51:3454-3463.
25. Onishi S, Kim Y, Nakayama H, Mansour AA 3rd, Lowe WR, Ollivier M. Infratubercle anterior closing wedge osteotomy corrects sagittal alignment without affecting coronal alignment or patellar height. *J Clin Med* 2024;13:4715.
26. Rozinthe A, van Rooij F, Demey G, Saffarini M, Dejour D. Tibial slope correction combined with second revision ACLR grants good clinical outcomes and prevents graft rupture at 7-15-year follow-up. *Knee Surg Sports Traumatol Arthrosc* 2022;30:2336-2341.
27. Tollefson LV, Kennedy NI, Banovetz MT, et al. Supratubercle anterior closing wedge osteotomy: No changes in patellar height and significant decreases in anterior tibial translation at 6 months postoperatively. *Am J Sports Med* 2024;52:1990-1996.
28. Cance N, Dan MJ, Pineda T, Demey G, DeJour DH. Radiographic investigation of coronal plane and patellar height and changes following tibial deflection osteotomy for correction of tibial slope in combination with ACL reconstruction. *Am J Sports Med* 2024;52:691-697.
29. Arun GR, Kumaraswamy V, Rajan D, et al. Long-term follow up of single-stage anterior cruciate ligament reconstruction and high tibial osteotomy and its relation with posterior tibial slope. *Arch Orthop Trauma Surg* 2016;136:505-511.
30. Dean CS, Chahla J, Matheny LM, et al. Posteromedially placed plates with anterior staple reinforcement are not successful in decreasing tibial slope in opening-wedge proximal tibial osteotomy. *Knee Surg Sports Traumatol Arthrosc* 2017;25:3687-3694.
31. Mayer P, Schuster P, Schlumberger M, et al. Effect of anterior tibial closing wedge osteotomy on coronal tibial alignment in relation to preoperative medial proximal tibial angle and wedge height. *Am J Sports Med* 2023;51:2567-2573.
32. Cance N, Dan MJ, Pineda T, Demey G, Dejour DH. Radiographic investigation of differences in static anterior tibial translation with axial load between isolated ACL injury and controls. *Am J Sports Med* 2024;52:338-343.
33. Dejour H, Bonnin M. Tibial translation after anterior cruciate ligament rupture. Two radiological tests compared. *J Bone Joint Surg Br* 1994;76:745-749.
34. Roberts J, Ness B, Cleland J, et al. Operative management for anterior cuciate ligament injury in patients over 40 years old yields increased clinical outcome: a systematic review. *Arthroscopy* 2023;39:812-826.
35. Shekhar A, Tapasvi S, van Heerwaarden R. Anterior closing wedge osteotomy for failed anterior cruciate ligament reconstruction: State of the art. *J Am Acad Orthop Surg Glob Res Rev* 2022;6.
36. Yamaguchi KT, Cheung EC, Markolf KL, et al. Effects of anterior closing wedge tibial osteotomy on anterior cruciate ligament force and knee kinematics. *Am J Sports Med* 2018;46:370-377.
37. Dean RS, DePhillipo NN, Chahla J, Larson CM, LaPrade RF. Posterior tibial slope measurements using the anatomic axis are significantly increased compared with those that use the mechanical axis. *Arthroscopy* 2021;37:243-249.
38. Weinberg DS, Williamson DF, Gebhart JJ, Knapik DM, Voos JE. Differences in medial and lateral posterior tibial slope: An osteological review of 1090 tibiae comparing age, sex, and race. *Am J Sports Med* 2017;45:106-113.