VIDEO

Effect of Slope-Reducing Tibial Osteotomy With Primary Anterior Cruciate Ligament Reconstruction on Clinical and Radiological Results in Patients With a Steep Posterior Tibial Slope and Excessive Anterior Tibial Subluxation

Propensity Score Matching With a Minimum 2-Year Follow-up

Daofeng Wang,*† MD, Menglinqian Di,*† MD, Tong Zheng,*† MD, Chengcheng Lv,*† MD, Yang Liu,*† MD, Guanyang Song,*† MD, and Hui Zhang,*†‡ MD
Investigation performed at Beijing Jishuitan Hospital, Capital Medical University, Beijing, China

Background: A steep posterior tibial slope (PTS) and excessive anterior tibial subluxation of the lateral compartment (ASLC) have been considered to be associated with inferior graft outcomes in primary anterior cruciate ligament (ACL) reconstruction (ACLR). Case series studies have demonstrated that combined slope-reducing tibial osteotomy can greatly improve knee functional scores and stability in revision ACLR. However, there is currently no comparative study evaluating the clinical benefits of osteotomy procedures in primary ACLR.

Purpose: To assess the feasibility of combined slope-reducing tibial osteotomy and primary ACLR in patients with a steep PTS and excessive ASLC and to explore the suitable threshold for osteotomy.

Study Design: Case series; Level of evidence, 4.

Methods: Between 2016 and 2022, of the 108 patients with ACL injuries who had a steep PTS ($\geq$15°) and a follow-up $\geq$2 years, 30 patients with excessive ASLC ($\geq$6 mm) underwent concomitant slope-reducing tibial osteotomy and ACLR (osteotomy group), and 78 patients underwent isolated ACLR (control group). Propensity score matching at a 1:2 ratio was used to match preoperative variables between the 2 groups. After matching preoperative variables, 25 and 48 patients underwent combined surgery and isolated ACLR, respectively. The primary outcome was ACL graft status (failure and laxity rates). The secondary outcomes were ASLC and anterior tibial subluxation of the medial compartment (ASMC), KT-1000 arthrometer side-to-side difference (SSD), pivot-shift grade, and second-look arthroscopic findings. Stratified analysis was performed with 1° PTS increments to explore the osteotomy threshold.

Results: Both groups were comparable in terms of age, sex, side, body mass index, PTS, graft diameter, time from injury to surgery, ASLC, ASMC, KT-1000 arthrometer SSD, pivot-shift grade, and meniscal injuries (all $P > .05$). The mean PTS significantly decreased from 18.2° to 6.7° ($P < .001$) in the osteotomy group. The 2-year rate of ACL graft laxity was 12.0% in the osteotomy group and 35.4% in the control group, with a statistically significant difference ($P = .033$). There was no significant difference in the 2-year rate of ACL graft failure between the 2 groups (8.0% vs 12.5%, respectively; $P = .559$). The final follow-up data showed that improvements in ASLC (4.5 vs 6.4 mm, respectively; $P = .012$) and ASMC (2.8 vs 4.5 mm, respectively; $P = .014$) were more significant in the osteotomy group compared with the control group. On the second-look arthroscopic examination, the incidence of graft roof impingement in the control group was significantly higher than that in the osteotomy group (22.9% vs 4.0%, respectively; $P = .039$). No significant differences were observed between the 2 groups in terms of KT-1000 arthrometer SSD and high-grade pivot shift ($P > .05$). Furthermore, stratified analysis revealed that the combined procedure significantly reduced the ACL graft failure rate and improved the KT-1000 arthrometer SSD in patients with a preoperative PTS $\geq$16°.

The American Journal of Sports Medicine
2025;53(6):1381–1391
DOI: 10.1177/03635465251330976

Conclusion: Slope-reducing tibial osteotomy combined with primary ACLR significantly decreased the amount of anterior tibial subluxation, the incidence of graft roof impingement, and the graft laxity rate for patients with a steep PTS (≥15°) and excessive ASLC (≥6 mm). Furthermore, in patients with a PTS ≥16°, the combined procedure improved anterior knee stability and reduced the graft failure rate. Therefore, a PTS ≥16° plus ASLC ≥6 mm may be considered an appropriate indication for combining slope-reducing tibial osteotomy with primary ACLR.

Keywords: posterior tibial slope; slope-reducing tibial osteotomy; osteotomy threshold; residual graft laxity; anterior tibial subluxation; knee stability

Despite continuous improvements in surgical techniques for anterior cruciate ligament (ACL) injuries, the failure rate of primary ACL reconstruction (ACLR) remains between 11% and 20%.[30] The causes of ACLR failure are multifactorial. Recently, great attention has been focused on inherent bony morphology that correlates with an increased risk of ACLR failure. Among the numerous bony variations, there is growing evidence that a steep posterior tibial slope (PTS) adversely affects knee kinematics.[11,20] An increased PTS generates a greater anterior shear force when an axial load is applied to the knee, leading to anterior tibial subluxation of the lateral compartment (ASLC).[11] In patients experiencing failed ACLR, both a steep PTS and excessive ASLC are common findings.[4,15-17]

Consequently, combined tibial osteotomy to reduce a steep PTS has been advocated during revision ACLR to protect the revised ACL graft.[1,8,19,29,33] Corresponding clinical results have supported the effectiveness of this combined procedure in decreasing a steep PTS, improving knee stability, and minimizing recurrent failure. Considering the invasive and complex nature of osteotomy, there is currently a paucity of literature examining the outcomes associated with this combined procedure in patients with ACL injuries. However, for patients with an inherently high risk for graft failure, including a steep PTS and excessive ASLC, the addition of slope-reducing tibial osteotomy is potentially beneficial to prevent graft failure after primary ACLR.

To date, only one case series study has reported the short-term results of slope-reducing tibial osteotomy during primary ACLR, and the surgical indication was strictly controlled as a PTS >13° and ASLC >10 mm.[26] Within this patient cohort, along with a 10° reduction in the PTS, ACLR yielded satisfactory subjective scores, no residual pivot shift, no graft reruptures, and a dramatic decrease in ASLC at 2 years postoperatively. To further elucidate the advantages of combined osteotomy compared with isolated ACLR in complex cases with ACL injuries, direct comparative analyses are required.

The purpose of this study was therefore to (1) compare the clinical, radiological, and arthroscopic results between combined slope-reducing tibial osteotomy versus isolated ACLR in patients with a steep PTS and excessive ASLC and (2) establish an appropriate threshold of the PTS for slope-reducing tibial osteotomy.

METHODS

Patient Enrollment

This study was approved by the Ethics Committee of Beijing Jishuitan Hospital, Capital Medical University, and we obtained informed consent from the enrolled patients. From June 2016 to June 2022, a continuous sample of patients with a clinically diagnosed ACL injury who underwent primary ACLR at our center was retrospectively reviewed. Only patients with a preoperative PTS ≥15° and ASLC ≥6 mm were included. Exclusion criteria were as follows: (1) partial ACL injury, (2) bilateral ACL injury, (3) combined posterior cruciate ligament injury or grade 3 medial collateral ligament injury, (4) preoperative hyperextension >10° of the injured knee, (5) mild to severe coronal-plane malalignment (varus/valgus >5°) of the injured lower extremity, (6) history of surgery to the lower extremities, and (7) final follow-up <2 years. Patients with a grade 1 or 2 medial collateral ligament injury and meniscal injury, followed by meniscectomy or meniscal repair, were not excluded. The mean age of the included patients was 29.5 years (range, 14-40 years), with 71% being male. Most injuries were noncontact and occurred during sports activities. The patient selection process is illustrated in Figure 1.

Grouping and Matching

During the recruitment period, all patients with a steep PTS (≥15°) and excessive ASLC (≥6 mm) were informed

‡Address correspondence to Hui Zhang, MD, Sports Medicine Service, Beijing Jishuitan Hospital, Capital Medical University, No. 31, Xinjiekou East Street, Beijing, 100035, China (email: zhui76@126.com).

*Sports Medicine Service, Beijing Jishuitan Hospital, Capital Medical University, Beijing, China.

†Beijing Research Institute of Traumatology and Orthopaedics, Beijing, China.

D.W., M.D., and T.Z. contributed equally to this article.

Submitted October 23, 2024; accepted February 14, 2025.

One or more of the authors has declared the following potential conflict of interest or source of funding: This study was supported by the National Natural Science Foundation of China (82002288 and 82172514) and the Beijing Hospitals Authority Youth Program (QML20230402). AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

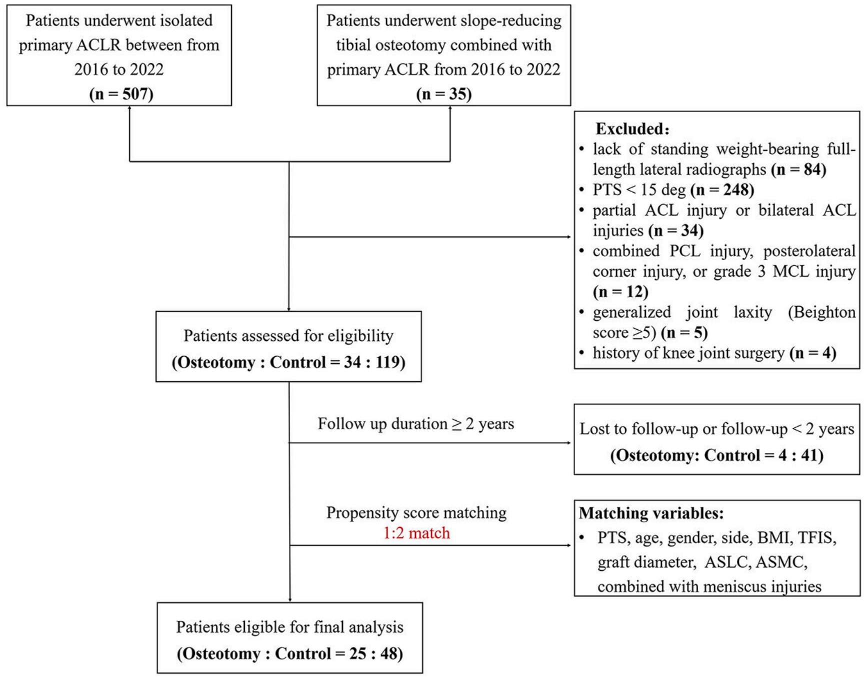

Figure 1. Flow chart of patient enrollment. ACLR, anterior cruciate ligament reconstruction; ASLC, anterior tibial subluxation of the lateral compartment; ASMC, anterior tibial subluxation of the medial compartment; BMI, body mass index; MCL, medial collateral ligament; PCL, posterior cruciate ligament; PSM, propensity score matching; PTS, posterior tibial slope; TFIS, time from injury to surgery.

about the surgical strategy to reduce the PTS and voluntarily chose to undergo osteotomy or not. Because of the nonrandom grouping method, propensity score matching was used to reduce the selection bias and the effect of confounding factors. Patients who underwent combined slope-reducing tibial osteotomy (osteotomy group) were matched 1:2 with those who underwent isolated ACLR (control group) based on age, sex, side, body mass index (BMI), time from injury to surgery (TFIS), graft diameter, meniscal status, preoperative PTS, and ASLC in extension (Figure 1).

Surgical Technique

ACL Graft Preparation. Autograft harvesting involved making a vertical incision on the medial side of the tibial tubercle to expose the pes anserinus. The sartorius fascia was incised to expose the semitendinosus and gracilis tendons, which were harvested as grafts for ACLR. All patients underwent a single-bundle ACLR technique with an 8-strand graft configuration using FiberWire (Arthrex) for weaving and reinforcement.

Tibial Tunnel Placement. Arthroscopic surgery was performed through the anterolateral portal to access the joint. Using an ACL tibial guide, the joint was positioned at the center of the footprint of the ACL tibial attachment site. The tibial tunnel exit was placed at the level of the pes anserinus and approximately 4 cm from the medial tibial plateau (Figure 2A).

Slope-Reducing Tibial Osteotomy. At a distance of 2 cm from the highest point of the tibial tubercle, a 2-mm Kirschner wire (K-wire) was inserted, pointing toward the posterior cruciate ligament tibial attachment site. Then, another K-wire was inserted parallel to the first one, approximately 2 cm apart on the lateral side, and its position and direction were confirmed under fluoroscopy (Figure 2B). These 2 K-wires determined the upper osteotomy plane. The osteotomy angle was measured using a goniometer, and 2 additional K-wires were inserted to confirm their positions, converging on the posterior cortex of the tibia. These 2 K-wires determined the lower osteotomy plane. Lateral radiographs of the knee joint were taken to confirm the angle between the upper and lower osteotomy planes, which matched the preoperatively planned angle (Figure 2C). The self-designed osteotomy module in this study was set at 10°, with the correction range between 8° and 12°. Osteotomy was performed along the K-wires using an oscillating saw. After removing the wedge-shaped bone fragment, a bone chisel was used to partially cut the hinge of the posterior cortex of the tibia. Fluoroscopic confirmation was performed to ensure that the osteotomy depth reached the posterior cortex of the tibia (Figure 2D). Gradually extending the knee joint while applying pressure at the osteotomy site allowed for gradual closure of the osteotomy surface, avoiding potential fractures of the posterior tibial wall (Figure 2E). Fluoroscopic confirmation of the corrected PTS was followed by fixation using the TomoFix system (DePuy Synthes) (Figure 2F).

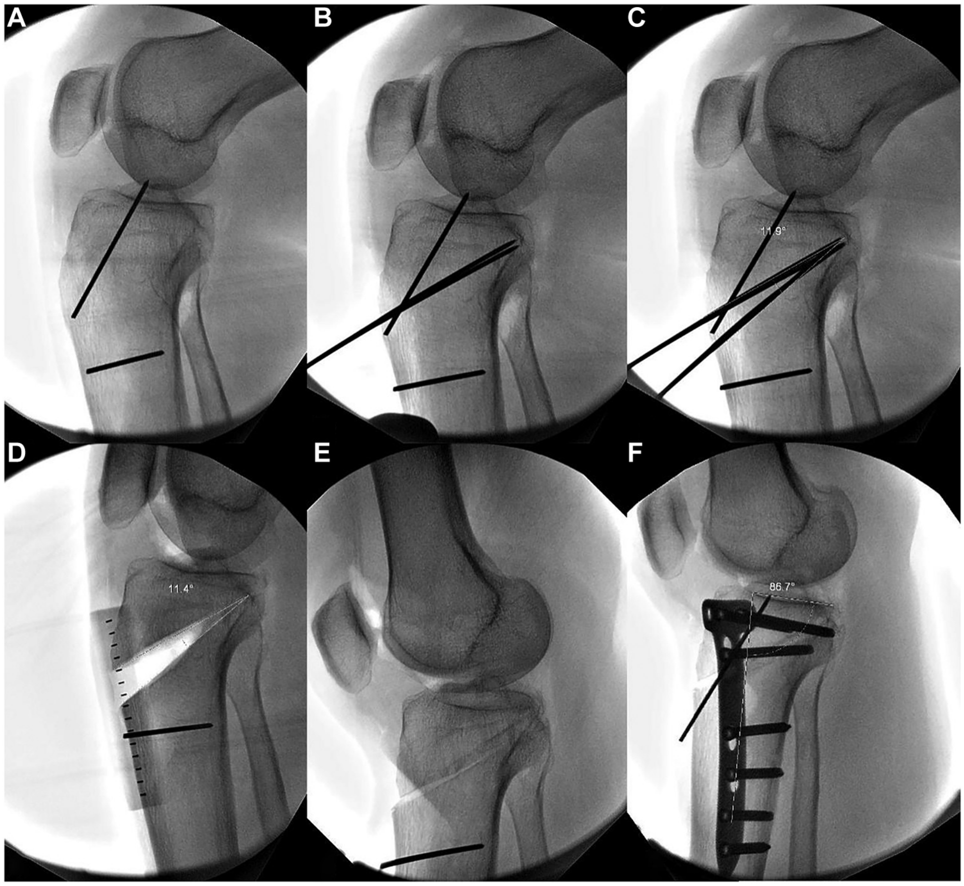

Figure 2. Slope-reducing tibial osteotomy. (A) The tibial tunnel position was identified under fluoroscopy. (B) Kirschner wires were used to determine the upper osteotomy plane at the distal tibial tuberosity, aiming toward the tibial insertion of the posterior cruciate ligament. (C) The lower osteotomy plane was defined based on the targeted posterior tibial slope. (D) Osteotomy was performed, and the wedge-shaped bone segment was removed. (E) The osteotomy site was compressed and closed, ensuring that the posterior tibial cortex remained intact. (F) The osteotomy site was fixed using a plate and screw system.

For details on high tibial osteotomy, please refer to the online Supplementary Video.

Femoral Tunnel Placement. Arthroscopic surgery was performed through the anteromedial portal, and a low anteromedial accessory portal was established. The knee joint was flexed at 120°, and a true lateral view of the knee joint was obtained under fluoroscopy. A guide pin was inserted through the anteromedial accessory portal to position the femoral tunnel using an inside-out technique. The tunnel diameter matched the size of the graft and had a depth of 20 mm.

Graft Insertion and Fixation. The XO Button system (ConMed Linvatec) was used for femoral-side fixation. Using a traction wire, the ACL graft was introduced into the tibial tunnel and then passed into the femoral tunnel. After confirming proper flipping and fixation of the XO Button, the joint was flexed 20 times to adjust the compliance of the graft. The graft was tensioned, maintaining the knee at 20° of flexion, and intratunnel fixation was performed in the tibial tunnel using the Intrafix sheath and screw system (DePuy Synthes). Subsequently, double fixation was achieved on the anterior cortex of the tibia using 4.5-mm AO/ASIF cortical screws and washers (DePuy Synthes). The graft sutures were secured by wrapping them around the screws and applying compression with the washers.

Other Arthroscopic Procedures. Any additional intra-articular injuries, such as meniscal tears, were addressed accordingly. Meniscal tears were repaired based on their characteristics, while complex or irreparable chronic meniscal tears or defects required debridement. The meniscal injury patterns and surgical details for both groups are provided in Appendix Table A1 (available in the online version of this article).

Rehabilitation Protocol

Progressive rehabilitation began immediately after surgery. A hinged knee brace was used for the first 4 weeks. The brace could be unlocked, allowing passive range of motion exercises from 0° to 90°. The knee joint was permitted to achieve full extension (0°), but hyperextension was avoided. Partial weightbearing started at 4 weeks

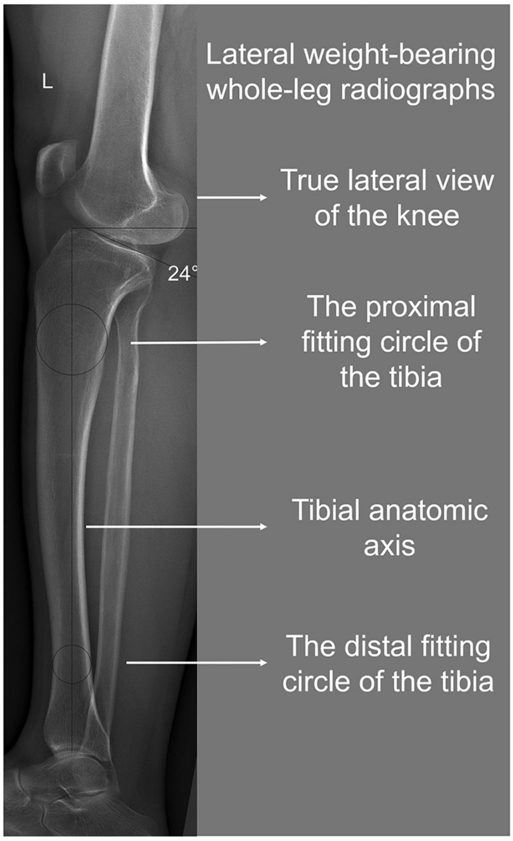

Figure 3. Measurement of the posterior tibial slope. On true lateral radiographs of the lower limb, best-fit circles were formed at the proximal and distal cortices of the tibia to determine the tibial anatomic axis. The angle between the tangent to the medial tibial plateau and a line perpendicular to the tibial anatomic axis was defined as the posterior tibial slope.

postoperatively, followed by full-weightbearing walking at 6 weeks. Gradual return to preoperative sports activities was expected within 9 to 12 months after surgery.

Data Collection

Age, sex, side, and BMI were recorded for all patients preoperatively. The timing of the initial ACL injury was established based on patient recollection, and TFIS represented the interval from the initial ACL injury to ACLR.

Physical Examination

A physical examination was performed with the patient under anesthesia before initial surgery and at the time of hardware removal (final follow-up). All examinations were conducted by the senior author (H.Z.), who has >20 years of orthopaedic experience. The KT-1000 arthrometer was used with maximal manual force and recorded the side-to-side difference (SSD). The pivot-shift test finding was graded as negative, 1 + (glide), 2 + (clunk), or 3 + (locking).

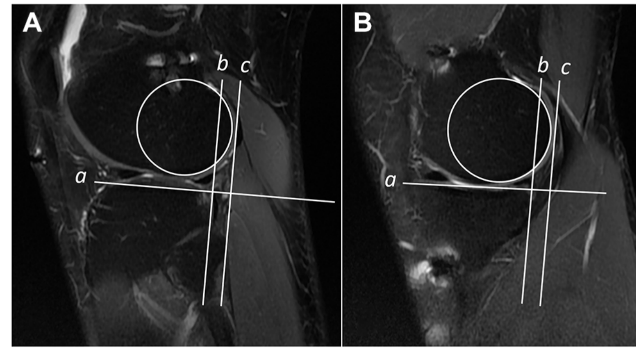

Figure 4. Anterior tibial subluxation of the (A) lateral and (B) medial compartments in extension. The circles in the diagram represent the best-fit circles of the subchondral bone of the posterior medial and lateral femoral condyles. Line *a* is the tangent to the tibial plateau. A line (line *b*) was drawn perpendicular to line *a* from the posterior margin of the tibial plateau, and another line (line *c*) was drawn perpendicular to line *a* from the posterior margin of the femoral condyles. The distance between these 2 parallel lines represents anterior tibial subluxation of the lateral compartment and anterior tibial subluxation of the medial compartment.

Measurement of PTS

Using the EOS system (EOS Imaging), anteroposterior and lateral weightbearing whole-leg radiographs were obtained for all patients preoperatively and for patients in the osteotomy group at the final follow-up. The measurement of the PTS was conducted on true lateral radiographs of the knee with fluoroscopic control to ensure superimposition of the femoral condyles. The PTS was determined as the angle between the tangent line of the medial tibial plateau and a line perpendicular to the tibial anatomic axis (Figure 3). This method, which provided a full-length view of the tibia, was deemed suitable.[22] In this study, 2 observers (M.D. and H.Z.) independently measured the PTS.

Measurement of Anterior Tibial Subluxation

All patients underwent 1.5-T magnetic resonance imaging (MRI) with the same protocol both preoperatively and at the final follow-up. The patients were positioned supine on the examination table, with a pillow placed under the entire lower extremity to support knee extension and maintain a neutral rotational position. Again, 2 independent researchers (M.D. and H.Z.) measured ASLC and anterior tibial subluxation of the medial compartment (ASMC) on T2-weighted sagittal sequences using the method described by Tanaka et al[32] (Figure 4). The accuracy of PTS, ASLC, and ASMC measurements in this study was 0.1°.

Second-Look Arthroscopic Surgery

At the final follow-up, a routine second-look arthroscopic examination was performed for all patients during hardware removal by the senior author (H.Z.). The assessment primarily focused on ACL graft continuity and tension. Moreover, the presence of graft roof impingement during passive knee motion was recorded based on the findings reported by Watanabe and Howell[36]: (1) fractured or guillotined bundles at the tibial insertion or (2) a cyclops lesion. Other combined injuries, such as intercondylar notch hypertrophy and cartilage damage, were also evaluated.

Definition of Graft Laxity and Failure

In this study, patients who had any of the following at the final follow-up were confirmed to have graft laxity: (1) a KT-1000 arthrometer SSD >3 mm or a positive pivot-shift test finding under anesthesia or (2) graft laxity with probing on second-look arthroscopic surgery. Graft failure was defined as complete discontinuity of graft fibers observed on follow-up MRI or second-look arthroscopic surgery.

Calculation of Sample Size

This study used the graft laxity rate as the basis for sample size calculation. In the pilot study, 10 patients in the osteotomy group and 20 patients in the control group were enrolled, and the minimum 2-year outcomes showed graft laxity rates of 21% and 40%, respectively. A contingency table was constructed, and the effect size for the chi-square test was 0.402. With an alpha of .05 and power $(1 - \beta)$ of 0.80, G*Power software (Version 3.1; Franz Paul) calculated the minimum sample size needed to detect a difference in the graft laxity rate to be 49 patients.

Statistical Analysis

All quantitative data were tested for normality. Normally distributed quantitative data were recorded as mean ± standard deviation, while nonnormally distributed data were recorded as median and interquartile range. Categorical variables were presented as frequencies and percentages. The differences in quantitative variables between groups were analyzed using *t* tests or Wilcoxon rank-sum tests, while differences in categorical variables were analyzed using chi-square tests or Fisher exact tests. Stratified analysis was conducted using the preoperative PTS in 1° increments to evaluate differences in clinical, radiological, and arthroscopic outcomes between groups. The intraclass correlation coefficient[34] and kappa statistic[21] were calculated to evaluate the reliability of the measurement methods adopted in this study. All statistical analyses were performed using the R package (Version 4.2.1) and SPSS software (Version 26.0; IBM). The significance level was set at .05.

RESULTS

Baseline Characteristics of Patients

Based on inclusion and exclusion criteria, 108 patients with a preoperative PTS ≥15° and a follow-up ≥2 years were enrolled, with 30 of them undergoing slope-reducing tibial osteotomy. Using propensity score matching at a 1:2 ratio, 25 patients in the osteotomy group and 48 patients in the control group were included in the final analysis. Patient characteristics are summarized in Table 1. After baseline matching, the 2 groups were comparable in terms of age, sex, side, BMI, TFIS, KT-1000 arthrometer SSD, pivot-shift grade, PTS, ASLC, ASMC, graft diameter, meniscal status, and follow-up period (all $P > .05$) (Table 1). Particularly, the mean PTS was 18.2° in the osteotomy group and 17.9° in the control group ($P = .458$).

Reliability and Accuracy of Measurements

The interobserver intraclass correlation coefficients for PTS, ASLC, and ASMC measurements were all >0.80, confirming that the assessment methods used in this study have high reproducibility. See Appendix Table A2 (available online) for more reliability analysis details.

Physical Examination Findings

The mean postoperative KT-1000 arthrometer SSD in the osteotomy group showed no significant difference compared with that in the control group (1.2 vs 2.2 mm, respectively; $P = .149$). The proportion of patients with a positive pivot shift postoperatively was 8.0% in the osteotomy group and 23.0% in the control group, with no significant difference ($P = .253$) (Table 2). Compared with preoperatively, the KT-1000 arthrometer SSD significantly decreased postoperatively in both the osteotomy group (7.8 vs 1.2 mm, respectively; $P < .001$) and the control group (7.6 vs 2.2 mm, respectively; $P < .001$). The proportion of patients with a 2+/3+ pivot-shift grade was also significantly reduced from preoperatively to postoperatively in the osteotomy group (76.0% vs 0.0%, respectively; $P < .001$) and the control group (60.5% vs 4.2%, respectively; $P < .001$) (Table 3).

Radiological Outcomes

The PTS significantly decreased from 18.2° ± 1.9° preoperatively to 6.7° ± 2.0° postoperatively ($P < .001$) in the osteotomy group. At the final follow-up, the osteotomy group had significantly less ASLC (4.5 vs 6.4 mm, respectively; $P = .012$) and ASMC (2.8 vs 4.5 mm, respectively; $P = .014$) compared with the control group (Table 2). Notably, patients who underwent combined osteotomy showed significantly decreased ASLC (7.6 to 4.5 mm, $P = .002$) and ASMC (5.1 to 2.8 mm, $P = .034$) from preoperatively to postoperatively. In contrast, those undergoing isolated ACLR had no effective correction of ASLC (6.7 to 6.4 mm, $P = .856$) and even a slight increase of ASMC (3.8 to 4.5 mm, $P = .051$) from preoperatively to postoperatively (Table 3).

TABLE 1
Baseline Characteristics of Patients[a]

	Before PSM			After PSM		
	Osteotomy (n = 30)	Control (n = 78)	*P* Value	Osteotomy (n = 25)	Control (n = 48)	*P* Value
Age, y	30.6 ± 7.3	29.1 ± 8.6	.404	29.7 ± 6.9	30.0 ± 8.9	.835
Male sex	23 (76.7)	54 (69.2)	.444	20 (80.0)	31 (64.6)	.173
Left side	12 (40.0)	40 (51.3)	.293	9 (36.0)	23 (47.9)	.456
BMI, kg/m^2	25.2 ± 2.9	24.0 ± 3.3	.098	24.9 ± 2.3	24.6 ± 3.4	.738
TFIS, wk	24 (3-96)	8 (2-48)	.186[b]	24 (3-48)	8 (2-48)	.265[b]
SSD (KT-1000), mm	8.1 ± 2.9	7.5 ± 2.3	.258	7.8 ± 2.8	7.8 ± 2.4	.987
Pivot-shift grade			.430			.428
Negative/1+	8 (26.7)	32 (41.0)		6 (24.0)	19 (39.6)	
2+	20 (66.7)	42 (53.8)		18 (72.0)	26 (54.2)	
3+	2 (6.7)	4 (5.1)		1 (4.0)	3 (6.3)	
PTS, deg	18.2 ± 1.9	17.3 ± 1.8	.016	18.2 ± 1.9	17.9 ± 1.9	.458
ASLC, mm	8.4 ± 3.4	5.9 ± 3.8	.008	7.6 ± 1.8	6.7 ± 2.3	.241
ASMC, mm	5.0 ± 3.2	3.6 ± 3.1	.064	5.1 ± 3.1	3.8 ± 3.2	.144
Graft diameter, mm	8.5 ± 0.6	9.2 ± 1.1	.002	8.5 ± 0.6	8.8 ± 1.1	.100
Lateral meniscal injury	10 (33.3)	43 (55.1)	.042	9 (36.0)	24 (50.0)	.324
Medial meniscal injury	21 (70.0)	32 (41.0)	.007	16 (64.0)	21 (43.8)	.101
Follow-up, mo	29.3 ± 3.7	27.9 ± 3.6	.252	29.6 ± 3.5	28.8 ± 3.4	.488

[a]Data are presented as mean ± SD, n (%), or median (interquartile range). ASLC, anterior tibial subluxation of the lateral compartment; ASMC, anterior tibial subluxation of the medial compartment; BMI, body mass index; PSM, propensity score matching; PTS, posterior tibial slope; SSD, side-to-side difference; TFIS, time from injury to surgery.
[b]Mann-Whitney *U* test.

TABLE 2
Outcomes at Final Follow-up[a]

	Osteotomy (n = 25)	Control (n = 48)	*P* Value
SSD (KT-1000), mm	1.2 ± 2.9	2.2 ± 2.5	.149
Pivot-shift grade			.253
Negative	23 (92.0)	37 (77.1)	
1+	2 (8.0)	9 (18.8)	
2+	0 (0.0)	2 (4.2)	
ASLC, mm	4.5 ± 3.6	6.4 ± 2.3	.012
ASMC, mm	2.8 ± 2.1	4.5 ± 2.6	.014
Graft roof impingement	1 (4.0)	11 (22.9)	.039
Graft laxity	3 (12.0)	17 (35.4)	.033
Graft failure	2 (8.0)	6 (12.5)	.559
Cartilage injury (grade 1)	3 (12.0)	11 (22.9)	.261
Cyclops lesion	1 (4.0)	6 (12.5)	.242
Intercondylar notch hypertrophy	2 (8.0)	9 (18.8)	.223

[a]Data are presented as mean ± SD or n (%). ASLC, anterior tibial subluxation of the lateral compartment; ASMC, anterior tibial subluxation of the medial compartment; SSD, side-to-side difference.

Second-Look Arthroscopic Findings

On the second-look arthroscopic examination, the incidence of graft roof impingement was significantly higher in the control group than that in the osteotomy group (22.9% vs 4.0%, respectively; *P* = .039). In the osteotomy group, no adverse events such as infections, nonunion, or hardware complications were reported at the osteotomy site.

Graft Laxity and Failure

At the final follow-up, the incidence of ACL graft laxity was 12.0% (3/25) in the osteotomy group and 35.4% (17/48) in the control group, with a significant difference (*P* = .033). The ACL graft failure rate was 8.0% and 12.5%, respectively, in the osteotomy group and control group, with no statistically significant difference (Table 2).

TABLE 3
Preoperative and Postoperative Outcomes[a]

	Osteotomy (n = 25)			Control (n = 48)		
	Preoperative	Postoperative	*P* Value	Preoperative	Postoperative	*P* Value
PTS, deg	18.2 ± 1.9	6.7 ± 2.0	<.001	17.9 ± 1.9	—	—
SSD (KT-1000), mm	7.8 ± 2.8	1.2 ± 2.9	<.001	7.8 ± 2.4	2.2 ± 2.5	<.001
Pivot-shift grade			<.001[b]			<.001
Negative	0 (0.0)	23 (92.0)		3 (6.3)	37 (77.1)	
1+	6 (24.0)	2 (8.0)		16 (33.3)	9 (18.8)	
2+	18 (72.0)	0 (0.0)		26 (54.2)	2 (4.2)	
3+	1 (4.0)	0 (0.0)		3 (6.3)	0 (0.0)	
ASLC, mm	7.6 ± 1.8	4.5 ± 3.6	.002	6.7 ± 2.3	6.4 ± 2.3	.856
ASMC, mm	5.1 ± 3.1	2.8 ± 2.1	.034	3.8 ± 3.2	4.5 ± 2.6	.051

[a]Data are presented as mean ± SD or n (%). ASLC, anterior tibial subluxation of the lateral compartment; ASMC, anterior tibial subluxation of the medial compartment; PTS, posterior tibial slope; SSD, side-to-side difference.
[b]Fisher exact test.

TABLE 4
Subgroup Analysis Based on Preoperative PTS[a]

	PTS ≥16°		
	Osteotomy (n = 20)	Control (n = 39)	*P* Value
ASLC, mm	4.3 ± 2.7	6.5 ± 2.3	.005
ASMC, mm	2.4 ± 1.6	4.4 ± 2.9	.016
SSD (KT-1000), mm	0.8 ± 2.5	2.4 ± 2.5	.023
Graft roof impingement	1 (5.0)	10 (25.6)	.036
Graft laxity	3 (15.0)	16 (41.0)	.035
Graft failure	0 (0.0)	6 (15.4)	.021
	PTS ≥17°		
	Osteotomy (n = 20)	Control (n = 33)	*P* Value
ASLC, mm	4.3 ± 2.7	6.3 ± 2.3	.012
ASMC, mm	2.4 ± 1.6	4.3 ± 3.1	.032
SSD (KT-1000), mm	0.8 ± 2.5	2.2 ± 2.1	.027
Graft roof impingement	1 (5.0)	8 (24.2)	.071
Graft laxity	3 (15.0)	15 (45.5)	.023
Graft failure	0 (0.0)	4 (12.1)	.046

[a]Data are presented as mean ± SD or n (%). ASLC, anterior tibial subluxation of the lateral compartment; ASMC, anterior tibial subluxation of the medial compartment; PTS, posterior tibial slope; SSD, side-to-side difference.

Threshold for Osteotomy

This study performed stratified analysis based on the preoperative PTS (in 1° increments), with the primary outcome being the graft failure rate to determine the clinical benefits of slope-reducing tibial osteotomy for different patient groups. The analysis indicated that in patients with a PTS ≥16°, combined osteotomy significantly reduced the graft failure rate and improved the KT-1000 arthrometer SSD (Table 4).

DISCUSSION

The main findings of this study can be summarized as follows. For patients with a PTS ≥15° and ASLC ≥6 mm, (1) combined slope-reducing tibial osteotomy with ACLR significantly decreased the amount of anterior tibial subluxation, the incidence of graft roof impingement, and the graft laxity rate compared with ACLR alone at a minimum 2-year follow-up, and (2) patients with a PTS ≥16° benefited significantly greater from the combined procedure in improving anterior knee stability and reducing the graft failure rate. To our knowledge, this is the first comparative study to investigate the benefits of combined slope-reducing tibial osteotomy with primary ACLR.

Clinical and biomechanical studies have consistently shown a strong correlation between a steep PTS and increased stress within the ACL, leading to graft failure.[2,6,8] Lee et al[17] found that patients with graft failure had a significantly greater preoperative PTS compared with those with intact grafts, which is consistent with the findings of Christensen et al[3] based on follow-up MRI. Causal analysis has demonstrated that the risk of graft failure after ACLR is 4.5 times higher in knees with a PTS >12° compared with knees with a relatively flat slope.[17] Multiple systematic reviews have also confirmed this association.[9,35,38] Yamaguchi and colleagues[37] measured changes in ACL forces and knee kinematics before and after anterior closing wedge tibial osteotomy in cadaveric specimens. Their study demonstrated that PTS-reducing osteotomy significantly decreased ACL forces and reduced anterior tibial subluxation for knee loads. Similarly, Imhoff et al[14] observed comparable results in their cadaveric study and concluded that osteotomy could protect ACL grafts in revision surgery. Clinically, slope-reducing tibial osteotomy is mainly used for revision ACLR scenarios, and related studies[1,7,8,19,29,33] have reported satisfactory clinical outcomes: good knee joint stability, high patient-reported functional scores, and low graft failure rates.

Whether osteotomy can be combined with primary ACLR remains uncertain. The surgical trauma caused by osteotomy needs to be carefully considered. Although surgical indications should be strictly limited, osteotomy may provide significant benefits for patients at a high risk of ACL graft failure, especially those with other risk factors related to a steep PTS. Several studies have also investigated the correlation between a steep PTS and anterior tibial subluxation. Giffin et al[11] found that when the PTS increased from an average of 8.8° to 13.2°, ASLC relative to the femur increased by approximately 3.6 mm using a robotic system. Similarly, Grassi et al[12] measured the anatomic parameters of the knee in patients with ACLR failure and found that an excessive PTS (>13°) exacerbated ASLC (>10 mm) during knee extension. Song et al[25,27,28] found that excessive (>10 mm) preoperative ASLC after an ACL injury was associated with inferior knee stability, a greater risk of graft roof impingement, and a high ACL graft failure rate. These findings suggest that a simultaneous increase in the PTS and ASLC may indicate the need for PTS-reducing osteotomy.

The study conducted by Song et al[26] preliminarily demonstrated the clinical benefits of slope-reducing tibial osteotomy in worst-case scenarios during primary surgery. After combining osteotomy, excessive ASLC was corrected, joint stability was significantly improved, and graft failure rates were notably reduced. The results of the present study indicate that for patients with both a steep PTS and excessive ASLC, combined slope-reducing tibial osteotomy significantly improved both ASLC (4.5 vs 6.4 mm, respectively; P = .012) and ASMC (2.8 vs 4.5 mm, respectively; P = .014), reduced graft roof impingement (4.0% vs 22.9%, respectively; P = .039), and lowered the ACL graft laxity rate (12.0% vs 35.4%, respectively; P = .033) compared with ACLR alone. Studies have shown that residual graft laxity after ACLR is associated with inferior subjective knee function and an increased risk of revision ACLR.[10,18] Cristiani et al[5] quantified residual graft laxity at 6 months after ACLR using the KT-1000 arthrometer SSD and categorized patients into 3 groups (SSD ≤2 mm, 3-5 mm, and >5 mm). A follow-up of up to 5 years revealed that the revision rates for the 3 groups were 3.8%, 6.6%, and 11.4%, respectively, with a statistically significant difference ($P < .05$). Compared with the SSD ≤2 mm group, patients with an SSD of 3-5 mm and >5 mm had a significantly increased risk of revision ACLR (hazard ratio, 1.42 and 2.61, respectively; both $P < .01$).[5] Similarly, Lindanger et al[18] found that patients with an SSD of 3-5 mm at 6 months after ACLR had an increased risk of revision surgery during a 25-year follow-up. In a recent large cohort study, Fiil et al[10] reported that high residual laxity (SSD >3 mm) at 1 year postoperatively was significantly associated with a higher revision rate within 2 years of initial surgery. These findings highlight the importance of restoring normal knee laxity during ACLR to reduce the risk of revision surgery.

The slope threshold for combining osteotomy with primary ACLR is unclear. Previous studies on revision ACLR have generally suggested that osteotomy can be considered for a PTS >12°.[1,8,19,29,33] It is considered that the osteotomy threshold should be more stringent during primary surgery. In addition, it should be noted that this study measured the PTS using whole-leg radiographs, which tend to yield results approximately 2° higher compared with short knee radiographs used in previous studies.[8,13,19,24,29,31]

Furthermore, Ni et al[22] analyzed 25 cases of ACLR failure (case-control study; 50 control cases) and found that patients with preoperative ASLC ≥6 mm were more likely to experience graft failure (odds ratio, 9.9; P = .006). Based on these important studies, the indication for slope-reducing tibial osteotomy in the present study was a PTS ≥15° combined with ASLC ≥6 mm. The results of stratified analysis in the current study showed that in patients with a PTS ≥16°, the addition of slope-reducing tibial osteotomy to primary ACLR significantly reduced the graft failure rate (0.0% vs 15.4%, respectively; P = .021) and further improved anterior knee stability compared with ACLR alone.

Another noteworthy finding is that the osteotomy procedure effectively reduced the incidence of graft roof impingement (4.0% vs 22.9%, respectively) compared with the control group, while there were no significant differences between the 2 groups in terms of cartilage damage, intercondylar notch hypertrophy, and cyclops lesions. The formation of graft roof impingement after ACLR is typically considered a technical issue. Watanabe and Howell[36] found that if the tibial tunnel of the ACL graft is positioned too anteriorly, it may lead to graft impingement with the femoral intercondylar notch. Despite ongoing efforts to optimize anatomic reconstruction clinically, the incidence of graft roof impingement remains between 2% and 27%.[23,36] The findings of the current study suggest that correcting an excessive slope may help to clarify the position of the ACL graft on the tibial side.

Limitations

This study had the following limitations. First, precise true lateral weightbearing whole-leg radiographs were not always easy to obtain because of the torsional variability of the lower extremities, which could compromise the reliability of PTS measurements. Second, patient-reported outcomes were not collected; thus, subjective knee function between the groups was not compared. Third, outcome assessors were not able to be blinded to surgical selections, as the trace of osteotomy was easily found by macroscopy and on MRI. Fourth, the retrospective nature of the study introduced selection bias, although propensity score matching was carefully applied to ensure comparability between the 2 groups. Fifth, although the rehabilitation protocols for both groups were consistent, differences in recovery speed may exist. This factor was not accounted for in this study and could potentially affect the results. Last, but not least, the follow-up period was relatively short, and more ACLR failures might occur with time.

CONCLUSION

Slope-reducing tibial osteotomy combined with primary ACLR significantly decreased the amount of anterior tibial subluxation, the incidence of graft roof impingement, and the graft laxity rate for patients with a steep PTS ($\geq$15°) and excessive ASLC ($\geq$6 mm). Furthermore, in patients with a PTS $\geq$16°, the combined procedure improved anterior knee stability and reduced the graft failure rate. Therefore, a PTS $\geq$16° plus ASLC $\geq$6 mm may be considered an appropriate indication for combined slope-reducing tibial osteotomy with primary ACLR.

A Video Supplement for this article is available online.

ORCID iDs

Daofeng Wang https://orcid.org/0000-0003-3278-4682
Hui Zhang https://orcid.org/0000-0001-8329-1920

REFERENCES

1. 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(14):3478-3485.
2. 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(2):296-302.
3. Christensen JJ, Krych AJ, Engasser WM, Vanhees MK, Collins MS, Dahm DL. Lateral tibial posterior slope is increased in patients with early graft failure after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2015;43(10):2510-2514.
4. Cooper JD, Wang W, Prentice HA, Funahashi TT, Maletis GB. The association between tibial slope and revision anterior cruciate ligament reconstruction in patients $\leq$21 years old: a matched case-control study including 317 revisions. *Am J Sports Med*. 2019;47(14):3330-3338.
5. Cristiani R, Forssblad M, Helito CP, Edman G, Eriksson K, Stålman A. A high grade of postoperative knee laxity is associated with an increased hazard of revision surgery: a cohort study of 4697 patients with primary ACL reconstruction. *Am J Sports Med*. 2024;52(8):1937-1943.
6. Dejour D, Pungitore M, Valluy J, Nover L, Saffarini M, Demey G. Tibial slope and medial meniscectomy significantly influence short-term knee laxity following ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(11):3481-3489.
7. Dejour D, Rozinthe A, Demey G. 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(10):4467-4473.
8. 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(10):2846-2852.
9. 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(5):1299-1309.e6.
10. Fiil M, Nielsen TG, Lind M. A high level of knee laxity after anterior cruciate ligament reconstruction results in high revision rates. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(10):3414-3421.
11. Giffin JR, Vogrin TM, Zantop T, Woo SL, Harner CD. Effects of increasing tibial slope on the biomechanics of the knee. *Am J Sports Med*. 2004;32(2):376-382.
12. Grassi A, Macchiarola L, Urrizola Barrientos F, et al. Steep posterior tibial slope, anterior tibial subluxation, deep posterior lateral femoral condyle, and meniscal deficiency are common findings in multiple anterior cruciate ligament failures: an MRI case-control study. *Am J Sports Med*. 2019;47(2):285-295.
13. Hinz M, Brunner M, Winkler PW, et al. The posterior tibial slope is not associated with graft failure and functional outcomes after anatomic primary isolated anterior cruciate ligament reconstruction. *Am J Sports Med*. 2023;51(14):3670-3676.
14. Imhoff FB, Mehl J, Comer BJ, et al. Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(10):3381-3389.
15. Jaecker V, Drouven S, Naendrup JH, Kanakamedala AC, Pfeiffer T, Shafizadeh S. Increased medial and lateral tibial posterior slopes are independent risk factors for graft failure following ACL reconstruction. *Arch Orthop Trauma Surg*. 2018;138(10):1423-1431.
16. Kamien PM, Hydrick JM, Replogle WH, Go LT, Barrett GR. Age, graft size, and Tegner activity level as predictors of failure in anterior cruciate ligament reconstruction with hamstring autograft. *Am J Sports Med*. 2013;41(8):1808-1812.
17. Lee CC, Youm YS, Cho SD, et al. Does posterior tibial slope affect graft rupture following anterior cruciate ligament reconstruction? *Arthroscopy*. 2018;34(7):2152-2155.
18. Lindanger L, Strand T, Mølster AO, Solheim E, Inderhaug E. Effect of early residual laxity after anterior cruciate ligament reconstruction on long-term laxity, graft failure, return to sports, and subjective outcome at 25 years. *Am J Sports Med*. 2021;49(5):1227-1235.
19. 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(13):3454-3463.
20. Marouane H, Shirazi-Adl A, Adouni M, Hashemi J. Steeper posterior tibial slope markedly increases ACL force in both active gait and passive knee joint under compression. *J Biomech*. 2014;47(6):1353-1359.
21. McHugh ML. Interrater reliability: the kappa statistic. *Biochem Med*. 2012;22(3):276-282.

22. Ni QK, Song GY, Zhang ZJ, et al. Steep posterior tibial slope and excessive anterior tibial translation are predictive risk factors of primary anterior cruciate ligament reconstruction failure: a case-control study with prospectively collected data. *Am J Sports Med*. 2020;48(12):2954-2961.
23. Noailles T, Chalopin A, Boissard M, Lopes R, Bouguennec N, Hardy A. Incidence and risk factors for cyclops syndrome after anterior cruciate ligament reconstruction: a systematic literature review. *Orthop Traumatol Surg Res*. 2019;105(7):1401-1405.
24. 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(7):2336-2341.
25. Song GY, Ni QK, Zheng T, Feng H, Zhang ZJ, Zhang H. Increased posterior tibial slope is associated with greater risk of graft roof impingement after anatomic anterior cruciate ligament reconstruction. *Am J Sports Med*. 2021;49(9):2396-2405.
26. 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(14):3486-3494.
27. Song GY, Zhang H, Zhang J, et al. Greater static anterior tibial subluxation of the lateral compartment after an acute anterior cruciate ligament injury is associated with an increased posterior tibial slope. *Am J Sports Med*. 2018;46(7):1617-1623.
28. Song GY, Zhang H, Zhang J, Zhang ZJ, Zheng T, Feng H. Excessive preoperative anterior tibial subluxation in extension is associated with inferior knee stability after anatomic anterior cruciate ligament reconstruction. *Am J Sports Med*. 2020;48(3):573-580.
29. 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(8):1873-1880.
30. Tabbaa A, Atkins M, Montalvo AM, et al. Lower ACLR failure rates in bone-soft tissue versus soft tissue-only allografts in adults: a systematic review and meta-analysis. *Am J Sports Med*. 2025;53(3):734-744.
31. Takahashi T, Watanabe S, Hino M, Takeda H, Ito T. Excellent short-term results of dome-shaped high tibial osteotomy combined with all-inside anterior cruciate ligament reconstruction. *J Exp Orthop*. 2023;10(1):69.
32. Tanaka MJ, Jones KJ, Gargiulo AM, et al. Passive anterior tibial subluxation in anterior cruciate ligament-deficient knees. *Am J Sports Med*. 2013;41(10):2347-2352.
33. 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(1):23259671221144786.
34. Wang D, Zhang Z, Cao Y, et al. Recurrent patellar dislocation patients with high-grade J-sign have multiple structural bone abnormalities in the lower limbs. *Knee Surg Sports Traumatol Arthrosc*. 2024;32(7):1650-1659.
35. Wang YL, Yang T, Zeng C, et al. Association between tibial plateau slopes and anterior cruciate ligament injury: a meta-analysis. *Arthroscopy*. 2017;33(6):1248-1259.e4.
36. Watanabe BM, Howell SM. Arthroscopic findings associated with roof impingement of an anterior cruciate ligament graft. *Am J Sports Med*. 1995;23(5):616-625.
37. 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(2):370-377.
38. Zeng C, Cheng L, Wei J, et al. The influence of the tibial plateau slopes on injury of the anterior cruciate ligament: a meta-analysis. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(1):53-65.