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original article

The application of proximal tibial anterior closing wedge osteotomy in anterior cruciate ligament reconstruction

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A R T I C L E I N F O

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A B S T R A C T

Introduction: Posterior tibial slope (PTS) plays a vital role in knee stability. PTS of more than 12° may be considered with increased strain on the native anterior cruciate ligament (ACL) fibers. To handle the instability caused by changes in PTS degree, Proximal Tibial Anterior Closing Wedge Osteotomy (PT-ACWO) is adopted by surgeons.
Methods: Between October 2015 and October 2019, our department conducted a retrospective analysis of patients who experienced anterior cruciate ligament reconstruction (ACLR) graft failures, with a particular focus on pathological PTS. The time from initial ACLR to revision ranged from 1 to 10 years, with a mean of 2.5 years. Radiological assessments of PTS were conducted, and outcomes were quantified using the International Knee Documentation Committee (IKDC) score, Lysholm score, and Tegner activity scale. The surgical technique and the use of 3D Patient-Specific Instrumentation (PSI) were outlined. Preoperative imaging included the use of Kirschner wires to establish tibial plateau reference points, and 3D-PSI was employed to guide the location and depth of the tibial osteotomy, which was performed obliquely. In a notable instance, a novel tibial tunnel was mapped out, and ortho-bridge system (OBS) fixation was utilized to ensure adequate space for the new tunnel.
Results: In a cohort of seven patients with a mean follow-up of 28.1 months, a significant reduction in PTS was noted postoperatively (median [interquartile range, IQR], from 15.27° [13.46°, 16.60°] to 6.25° [5.89°, 6.78°]; $P = 0.002$). IKDC score improved to 85.10 (80.25, 88.10), $P < 0.001$; the Lysholm score to 88.00 (73.00, 90.50), $P < 0.001$; and the Tegner score to 8.00 (7.20, 8.05), $P = 0.025$ at final follow-up. Skin incision healing delays occurred in two instances, yet achieved closure by six weeks. Radiographs at three months demonstrated faster bone healing in oblique osteotomies than transverse ones. Knee joint stability was maintained, with no additional complications or evidence of instability noted. Magnetic resonance imaging (MRI) confirmed graft integrity in all patients, without signs of enlargement or mispositioning at last observation.
Conclusion: An augmented PTS angle exceeding 12 may constitute a potential etiology for the failure of ACLR grafts. In such patients, the implementation of ACLR combined with PT-ACWO could mitigate the risk of surgical failure during initial ACLR or subsequent revision procedures.

1. Introduction

Damage to the anterior cruciate ligament (ACL) may result in knee instability and osteoarthritis. Therapeutic interventions range from surgical repair to reconstruction procedures. At present, ACL reconstruction (ACLR) is the treatment of choice for individuals with ACL injuries. Nevertheless, it carries the risk of complications and exhibits a failure rate between 1 % and 8 %.[1,2] Complications following ACLR encompass diminished athletic performance, dysfunction in the extensor mechanism of the graft, arthritis, and graft failure. Both patient-related factors and surgical techniques can lead to the failure of ACLR, despite ongoing improvements in surgical practices.[3] The issue of increased posterior tibial slope (PTS), a known risk factor for ACL graft rupture identified at a critical threshold of 12°, has not been adequately addressed.[4] Corrective surgery using anterior closing wedge osteotomy (ACWO) in combination with high tibial osteotomy (HTO) has been demonstrated to reduce stress on the ACL and anterior tibial translation, leading to favorable clinical outcomes, especially when used in conjunction with ACLR. Research has shown that each degree increase in medial or lateral PTS correlates with a 1.76- and 1.68-fold increase in

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the risk of ACLR graft failure, respectively.[5] Revision ACLR often involves concomitant procedures such as meniscal or chondral treatment, lateral extra-articular augmentation, or osteotomy.[6] Proximal tibial anterior closing wedge osteotomy (PT-ACWO) can reduce anterior laxity in patients with knee ligament instability by correcting PTS.[7–9] By reducing the PTS to normal values (9°–11° for the medial plateau and 6°–8° for the lateral plateau), anterior tibial translation can be lessened, which may provide a protective effect on the ACL graft and be beneficial for patients undergoing ACLR revision.[10,11] Therefore, anterior closing wedge osteotomy is used to correct an increased PTS that could lead to ACLR failure, surgically reducing the slope of the proximal tibia to provide biomechanical protection for the ACL graft.[12]

The 3D-Patient Specific Instrumentation (PSI) has been studied and applied in various orthopedic surgeries. Tailored to the patient's unique anatomical structure as determined by pre-surgical imaging, 3D-PSI enables surgeons to execute osteotomies with enhanced precision regarding both the location and angular adjustments.[13,14] This technology's application in high tibial osteotomy has been associated with increased surgical accuracy, reduced operative time, and improved clinical outcomes.

Upon excluding other risk factors and pinpointing an unusually increased PTS as a latent cause of ACLR failure, our investigation incorporated 7 cases where the knees undergoing ACLR graft failure due to elevated PTS were treated. We included a total of 7 knees treated for PTS-induced ACLR graft failure using 3D-PSI assisted PT-ACWO to correct the posterior tibial inclination. In the current study, we reported initial radiological and clinical outcomes, along with postoperative complications. We hypothesized that the integration of ACLR with 3D-PSI assisted PT-ACWO facilitates more precise anatomical positioning and guidance. The correction of abnormally elevated PTS is posited to protect the ACLR graft from stress-induced fatigue fractures, thereby reducing the risk of surgical failure in patients with increased PTS undergoing their initial ACLR or revision surgery.

2. Data and methods

2.1. General data

After gaining approval from the First People's Hospital of Kunming Review Committee, our team undertook a retrospective analysis of cases treated for ACLR graft failure and pathological PTS between October 2015 and October 2019. Within this timeframe, 7 patients underwent treatment for posterior tibial inclination correction with the aid of 3D-PSI assisted proximal tibial anterior closing wedge osteotomy. Patients were included in the study if they met the following criteria: (1) exhibited classic symptoms and signs of ACL rupture, with positive Lachman test and pivot-shift test results, confirmed by magnetic resonance imaging; (2) had a history of failed ACLR; (3) had preserved lateral compartment cartilage (International Cartilage Repair Society [ICRS] grades I or II); (4) demonstrated pathological PTS (defined as PTS ≥12°[15]). Additionally, patients were required to have a minimum follow-up period of two years.

Patients were excluded from the study if they had (1) normal PTS; (2) concomitant genu varum deformity; (3) laxity of the posterolateral structures. Individuals exhibiting a positive anterior drawer test in the tibial internal rotation position under anesthesia; (4) multi-ligament knee injuries; (5) severe osteoarthritis evident on knee radiographs; (6) if the primary ACLR was deemed to have failed due to technical errors during the initial surgery (Incorrect placement of the tibial and femoral tunnels.). Based on the inclusion and exclusion criteria, a total of 7 knees were enrolled in the study.

2.2. Radiological evaluation

The X-ray assessment encompassed weight-bearing anteroposterior knee views in the Rosenberg position, sagittal views at 30° flexion, and full-length weight-bearing anteroposterior and lateral views of the lower extremities, ensuring the femoral condyles overlaid with a maximum 0.5 cm gap at the tibial spine posterior border. The PTS was measured on X-ray as the angle between the line tangent to the medial tibial plateau's anterior and posterior margins and the perpendicular to the tibial mechanical axis (Fig. 1A).[15,16] The PTS was calculated using previously established measurement techniques from plain films.[17]

2.3. Pre-operative ppreparation

Preoperative planning utilized full-length standing anteroposterior radiographs of the lower extremities, setting a target PTS of 7°.[5] The intraoperative wedge osteotomy angle was determined by subtracting the target PTS from the preoperatively assessed PTS. The wedge osteotomy's upper entry point was identified as the lower edge of the tibial tuberosity, based on preoperative CT scans and 3D-CT reconstructions of the proximal tibia. The 3D-PSI for the osteotomy, provided by Aplus Company, was customized according to the planned wedge angle and 3D CT data (Fig. 1B). Adjustments were made to the osteotomy cuts' orientation, maintaining the initial upper entry point but angling the cuts towards the posterior superior border of the proximal tibia, near the posterior cruciate ligament's tibial insertion. The osteotomy guide was precisely aligned against the medial proximal tibia, indicating patient specifics, osteotomy depth, and distance from the guide's top to the medial tibial plateau, including two slots aimed at the tibia's posterior edge (Fig. 1C left). The 3D-PSI was positioned on the anterior margin of the proximal tibia (Fig. 1C right).

2.4. Postoperative management

In the immediate postoperative protocol for this cohort, lower limb orthoses were utilized for stabilization, with a strict non-weight bearing directive for the initial six weeks. Rehabilitation exercises, including passive and active knee mobility drills, ankle pumps, and leg lifts, were initiated on the first postoperative day. At the six-week mark, patients were reassessed and commenced on progressive weight-bearing routines, culminating in full weight-bearing capacity three months post-surgery. Half a year into recovery, a gradual reintroduction to non-rotational sports was recommended. By the ninth month, engagement in non-contact, rotational sports became permissible, leading to full sports participation at the one-year recovery milestone.

2.5. Postoperative efficacy evaluation criteria

The functional assessment before and after surgery included scoring according to the International Knee Documentation Committee (IKDC), Lysholm knee scoring scale, and the Tegner activity level scale.[18]

2.6. Statistical analysis

Those not normally distributed were summarized using median and interquartile range (IQR) for radiological variables. Given the small number of participants and the inability to assume a normal distribution, the non-parametric Mann-Whitney U test was used to compare preoperative and postoperative PTS, IKDC score, Lysholm score and Tegner score, with a P-value of <0.05 considered statistically significant. A single evaluator performed radiographic measurements on baseline X-rays at two separate time points, spaced several weeks apart, to assess post-surgical consistency. During the reassessment, the evaluator was blinded to the initial measurement results. Subsequently, three independent evaluators measured the same X-rays to determine inter-rater consistency. The statistical analyses were carried out using the R software (Version 4.0).

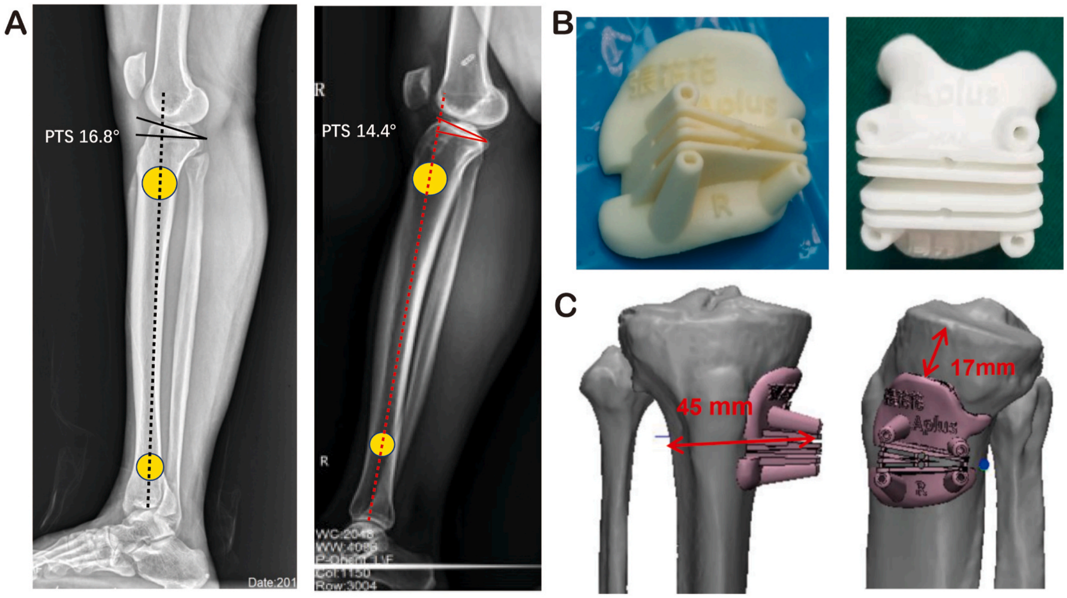

Fig. 1. Visualization of PTS measurement and 3D-PSI in tibial osteotomy. A. The methodology for measuring the PTS, defined as the angle between the tangent to the apexes of the anterior and posterior borders of the medial tibial plateau and the perpendicular to the mechanical axis of the tibial shaft on full-length lateral radiographs. B. Refined prototype of 3D-PSI. C. Modeled representation of 3D-PSI placement and osteotomy specifications on the tibia.

3. Results

3.1. Subjects

In this case series, seven patients met the inclusion and exclusion criteria and were followed up postoperatively. The group consisted of 2 male and 5 female patients, with follow-up periods ranging from 24 to 32 months, averaging 28.1 months. The average age of the patients at the time of surgery was 34 years (ranging from 25 to 58 years). The time interval between the previous ACLR and the revision surgery ranged from 1 to 10 years, averaging 2.5 years. From the pre-operative to the post-operative period, there was a significant reduction in the PTS, with the median [interquartile range] decreasing from 15.27(13.46, 16.60) to 6.25 (5.89, 6.78), $P = 0.02$(Table 1).

3.2. Operative procedure

General anesthesia was administered for all procedures, with patients positioned supine. A thigh tourniquet was utilized, and sideboards were strategically positioned laterally and distally to facilitate knee flexion at 90° without impeding motion. Arthroscopic evaluation of the ACL graft, cartilage, and menisci was conducted via anterolateral and anteromedial portals.

The PT-ACWO procedure entailed creating an oblique medial longitudinal incision, 6–8 cm in length, slightly medial to the tibial tuberosity, with conservation of full-thickness skin flaps for periosteal elevation and exposure of the patellar tendon's tibial insertion. Dissection of the deep medial collateral ligament (MCL) and fascia from the tibia posteriorly enabled the placement of protective soft tissue guards and a Hoffman retractor. Preoperative 3D-PSI fabrication determined the precise osteotomy level below the patellar tendon's inferior attachment border.

A 1.0 mm Kirschner wire (K-wire) was used to mark the horizontal reference point on the tibial plateau. The 3D-PSI was then accurately positioned against the medial tibia, verified by proper fitting of its surfaces to the bone (Fig. 2A). K-wires can be inserted into the pre-established nail holes within the two osteotomy slots (Fig. 2B). Arthroscopic guidance confirmed the posterior hinge point did not breach the

Tabel 1
Basic information of patients and postoperative PTS changes and scales.

Number	Sex	Age (years)	Height (cm)	Weight (kg)	Surgical Procedures	Pre-operative	Post-operative	Pre-operative	Post-operative	Pre-operative	Post-operative	Pre-operative	Post-operative
						PTS		IKDC score		Lysholm score		Tegner score	
Case1	Male	27	173	72	1	17.2	7	55.6	96.3	61	98	8.8	8.7
Case2	Female	31	166	54	2	14.5	3.4	49.3	85.1	55	89	8.4	6.5
Case3	Male	25	177	85	2	16.6	6.1	51.5	89.8	58	92	8.9	8
Case4	Female	58	156	68	1	12.41	8.99	36.8	75.6	36	69	7.1	5.1
Case5	Female	31	156	70	1	15.27	6.56	50.2	82.9	47	71	8.7	8.0
Case6	Female	31	165	65	2	10.99	5.69	52.1	86.4	44	75	8.9	7.9
Case7	Female	35	160	53	1	16.6	6.25	49.6	77.6	50	88	9.0	8.1
Median (Q_1, Q_3)		31.00 (29.00, 33.00)	165.00 (158.00, 169.50)	68.00 (59.50, 71.00)		15.27 (13.46, 16.60)	6.25 (5.89, 6.78)	50.20 (49.45, 51.80)	85.10 (80.25, 88.10)	50.00 (45.50, 56.50)	88.00 (73.00, 90.50)	8.80 (8.55, 8.90)	8.00 (7.20, 8.05)
Statistic						$Z = -3.07$		$Z = -3.44$		$Z = -3.44$		$Z = -2.24$	
P						0.002		<0.001		<0.001		0.025	

Q_1: 1st Quartile, Q_3: 3rd Quartile.
Z: Mann-Whitney test.
Surgical Procedures:1:High anterior closed-wedge osteotomy of the proximal tibia on the right side, arthroscopic anterior cruciate ligament revision2:High anterior closed-wedge osteotomy of the proximal tibia on the left side, arthroscopic anterior cruciate ligament revision.

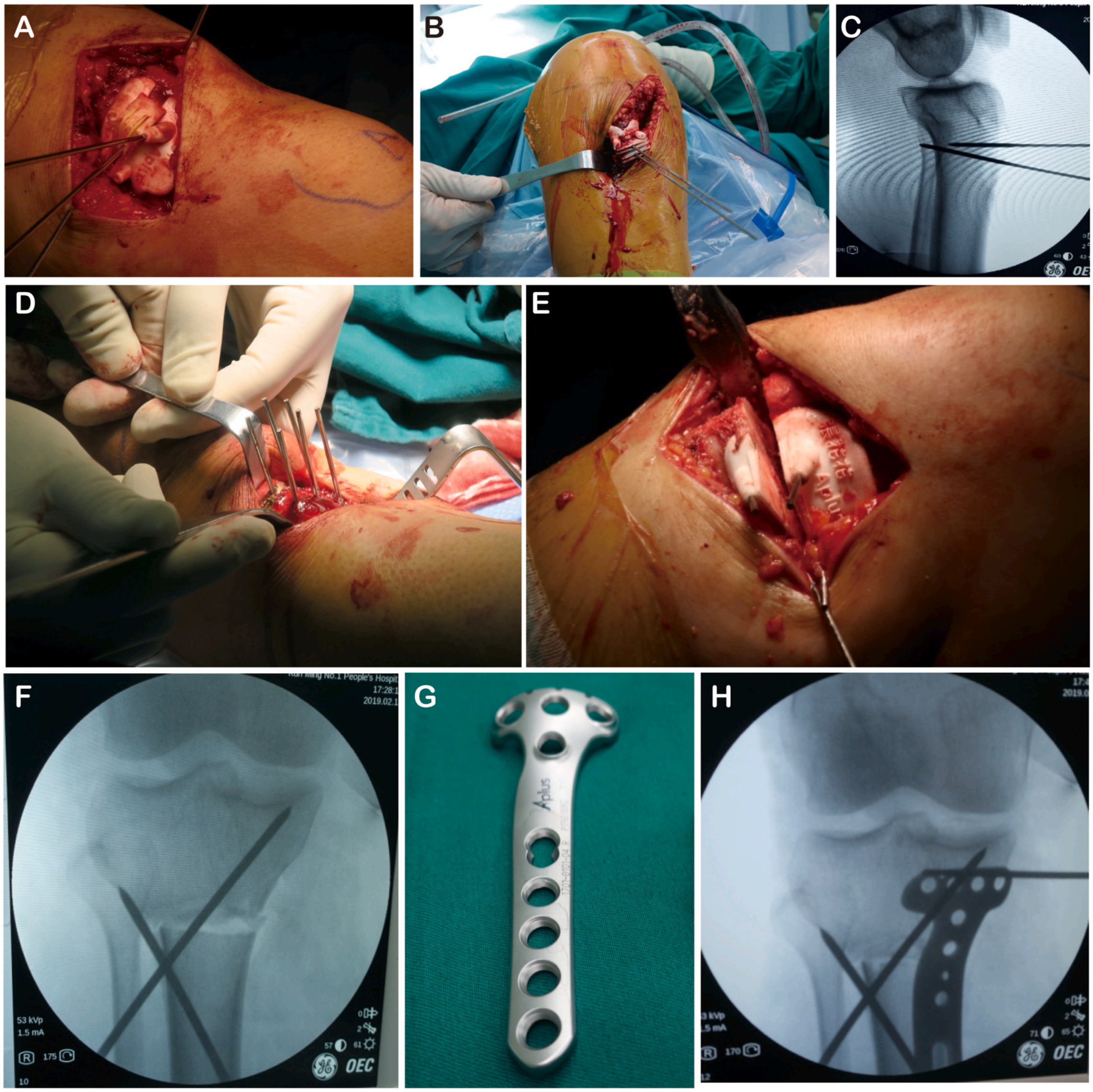

Fig. 2. Sequential steps in tibial osteotomy utilizing 3D-PSI. A. Positioning of the 3D-PSI on the tibial osteotomy surface. B. Insertion of kirschner wires through osteotomy groove. C. Confirmation of posterior osteotomy hinge point via arthroscopy. D. Securement of 3D-PSI with four kirschner wires. E. Removal of the wedge-shaped bone block post-osteotomy. F. Closure of anterior opening with kirschner wire fixation. G. Application of the selected osteotomy fixation plate. H. Post-fixation status with osteotomy plate.

posterior cortex, crucial for maintaining structural integrity and protecting posterior neurovascular elements (Fig. 2C). The 3D-PSI was secured with four K-wires through pre-set fixation holes (Fig. 2D), ensuring that the 3D-PSI did not shift during the osteotomy. Osteotomy was performed with an oscillating saw and, when near the hinge, completed with an osteotome to ensure the posterior cortex remained intact (Fig. 2E).

Following osteotomy, manual knee extension was applied to close the gap, and the osteotomy was fixed using K-wires at a 7° PTS (Fig. 2F). An Aplus custom tibial osteotomy plate, commonly used by our team for medial compartment osteoarthritis, was then accurately placed and fixed under arthroscopic observation (Fig. 2G, Fig. 2H), offering reliable fixation as evidenced in follow-ups.

To mitigate the risks associated with transverse tibial osteotomy, we refined the orientation of the osteotomy line. The osteotomy was directed below the tibial insertion of the posterior cruciate ligament, toward the posterior superior edge of the proximal tibia (Fig. 3A). The 3D-PSI was positioned in line with this modified approach, bridging the anterior border of the proximal tibia and providing medial and lateral fixation points on the tibial crest for the oscillating saw, enhancing its penetration of the cortical bone (Fig. 3B).

For osteotomy gap closure, we employed 3.0 Kirschner wires inserted bidirectionally along the tibial crest for secure fixation (Fig. 3C). This technique reduced the probability of osteotomy surface displacement during plate adjustment as seen with arthroscopy, in contrast to the transverse approach (Fig. 3D, E). To address potential anterior gap nonclosure, we utilized two hollow screws for compressive fixation, which were required to transverse the posterior cortex for optimal compression (Fig. 3F). The fixation plate used was analogous to that in transverse osteotomy (Fig. 3G, H).

3.3. *Strategies for tunnel creation and bone grafting during ACLR*

For the tibial tunnel, three instances utilized an anterior approach, three involved the construction of a standard new tunnel, and one case applied a truncated wedge-shaped bone graft for tunnel grafting. When addressing the femoral tunnel, five cases employed an anterior tunnel, while two necessitated the establishment of a new tunnel. The

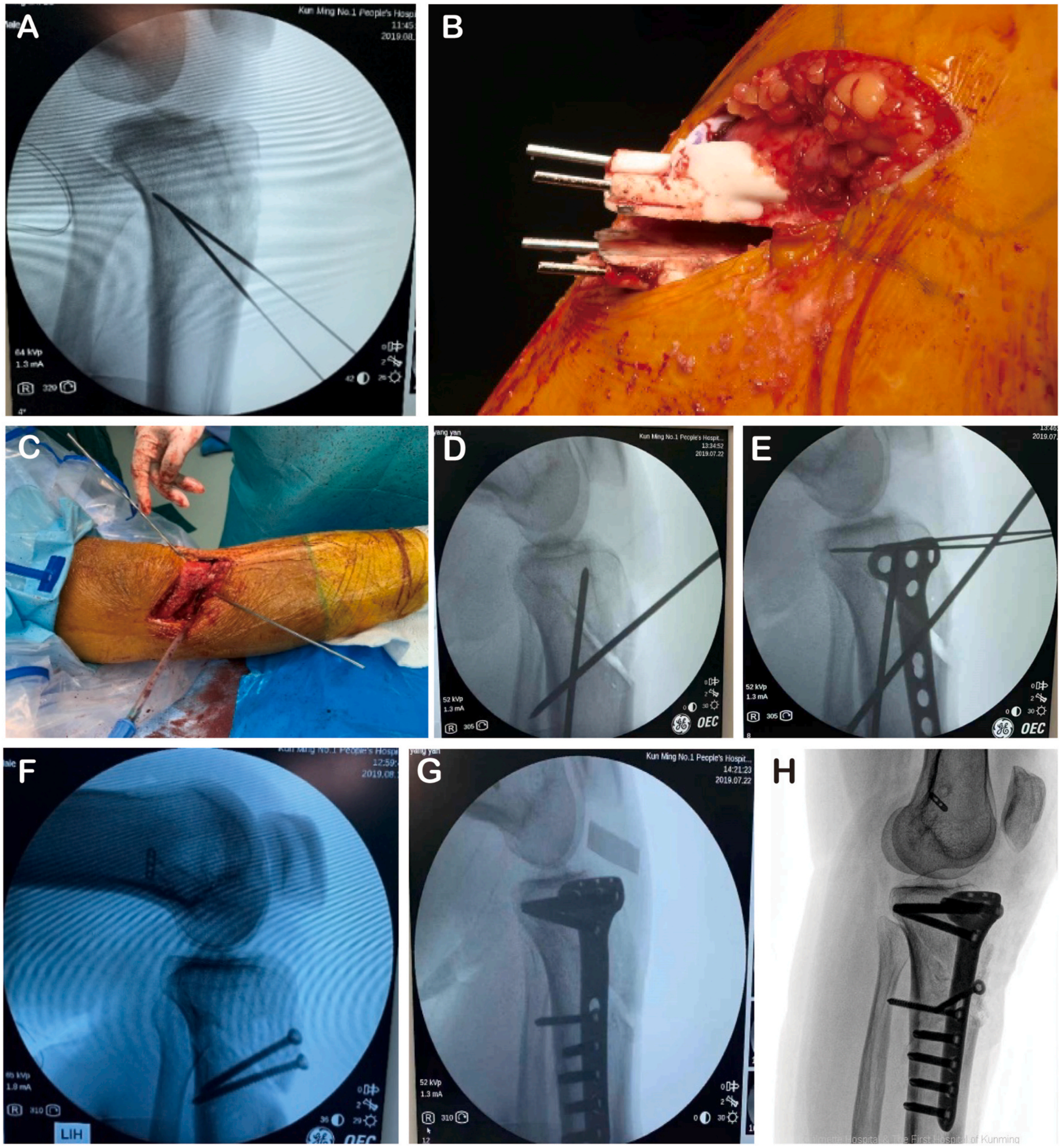

Fig. 3. Enhanced tibial osteotomy procedure with 3D-PSI, kirschner wire fixation, and arthroscopic validation. A. Revised osteotomy line direction with updated 3D-PSI. B. Positioning of 3D-PSI after anterior tibial edge osteotomy. C. Post-osteotomy closure with kirschner wire fixation. D. Arthroscopic visualization of osteotomy gap closure. E. Arthroscopically guided adjustment of steel plate. F. Hollow screw application for osteotomy gap compression and stabilization. G. Arthroscopic confirmation of post-fixation osteotomy plate status. H. Tibial site three months post-procedural intervention.

decommissioned anterior tunnels were consistently filled using truncated wedge-shaped bone grafts. Specifically, in Case 3, an expansion of the anterior tibial tunnel's external aperture and a hardening of the tunnel's inner bone wall prompted the consideration of a new tibial tunnel. However, the subsequent placement of the osteotomy fixation plate precluded the creation of a new tibial tunnel due to spatial constraints. Consequently, an osteotomy buttress screw (OBS) fixation system was employed (Fig. 4A), which provided robust fixation at the osteotomy site and facilitated the creation of space for a new tibial tunnel (Fig. 4B). This series ensured that osteotomy and ACLR were performed in a single operative session, with ACLR invariably following the osteotomy. The preoperative planning was individualized to allow for the spatial requirements of the tibial tunnel. Additionally, the post-osteotomy sequence permitted a reassessment of the anterior tibial tunnel's position after adjusting for the posterior tibial slope.

In the context of ACLR, graft selection was contingent upon the site of previous graft harvest and the status of the existing tunnels. In Case 1, a quadriceps tendon graft with a bone block from the surgical side was utilized, with fixation achieved via a titanium plate on the femoral side and a composite interference screw on the tibial side (Fig. 4C). Case 5 employed a bone-tendon-bone (BTB) graft from the surgical side (Fig. 4D), secured with a composite interference screw on the tibial side and titanium plate suspension on the femoral side (Fig. 4E, F). The remaining five cases underwent reconstruction using the contralateral semitendinosus tendon, with three opting for an all-inside ACLR.

During the follow-up period, delayed healing of the osteotomy site skin incision was observed in Cases 5 and 6, yet both cases achieved closure within six weeks. Radiological evidence indicated osseous union at the osteotomy sites within three months for all cases. Notably, the five cases with oblique osteotomies exhibited more rapid healing compared to Cases 5 and 7, which had transverse osteotomies. Throughout the follow-up, all knees exhibited no signs of instability. No further

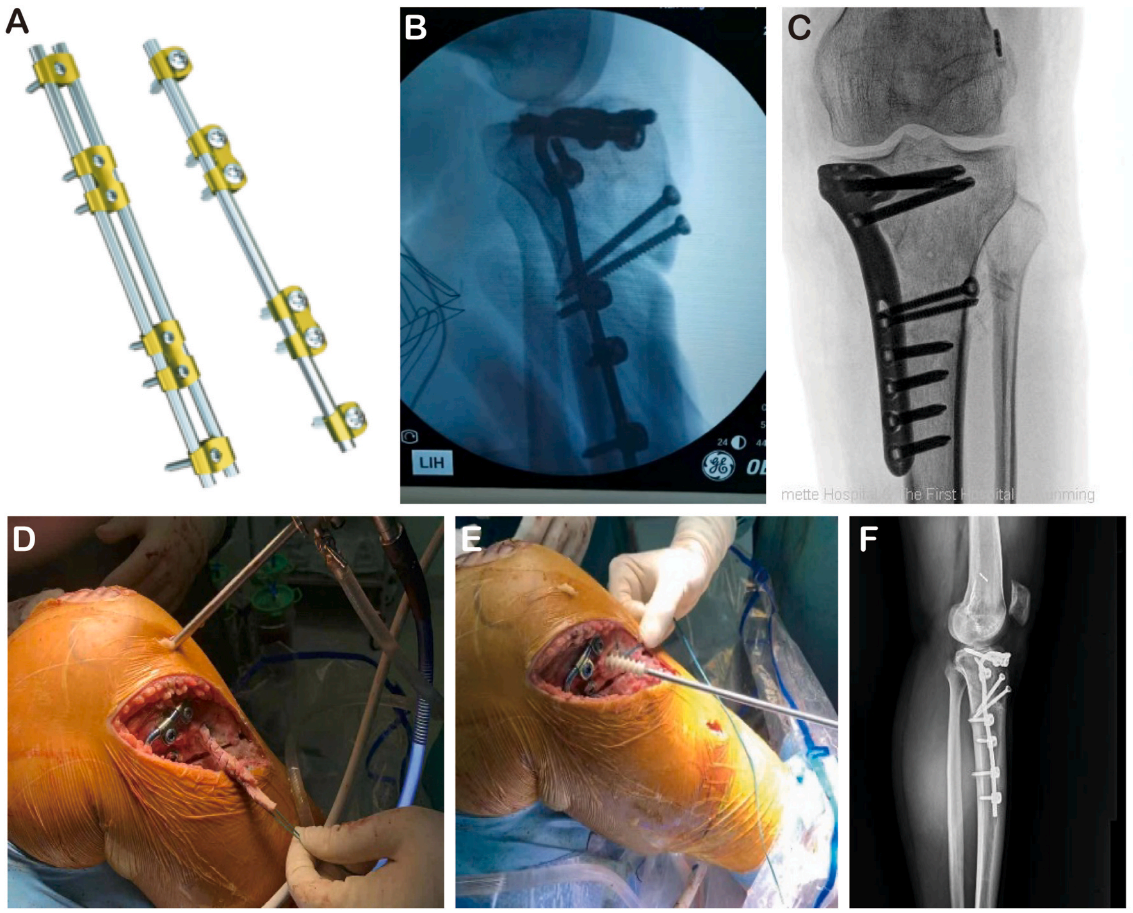

Fig. 4. Visualization of osteotomy fixation and grafting techniques. A. Schematic representation of the OBS fixation system. B. OBS system application post-osteotomy. C. Imaging of fixation utilizing composite compression screws. D. BTB (Bone-Tendon-Bone) graft representation. E. Tibial side fixation with composite absorbable compression screws. F. Lateral knee joint imaging post-surgery.

complications were detected in any of the cases.

3.4. Objective knee evaluation

The subjective IKDC scores demonstrated a significant improvement from a preoperative median of 50.20 points (IQR: 49.45, 51.80) to a median of 85.10 points (IQR: 80.25, 88.10) at the final postoperative follow-up ($P < 0.001$). Similarly, Lysholm scores showed substantial enhancement, with the preoperative median being 50.00 points (IQR: 45.50, 56.50) compared to the postoperative median score of 88.00 (IQR: 73.00, 90.50) at the last follow-up ($P < 0.001$).

During the final follow-up, the results of the Lachman test and the pivot-shift test of seven cases were all negative. Compared to the unaffected side, the range of motion of the affected knee was not limited. During the final follow-up, MRI reexamination indicated that the graft of all seven cases was in place without widened diameter or abnormal course observed.

3.5. Physical activity level

At the final follow-up, the median of Tegner activity score was 8.00 (IQR:7.20, 8.05), Preoperative score was 8.80 (IQR:8.55, 8.90),$P = 0.025$. During the final follow-up, case3 regained its pre-injury activity level, but the other six did not.

Preoperative and postoperative IKDC score, Lysholm score and Tegner score were available in 7 patients and are summarized in Table 1.

4. Discussion

Our research supports the evidence that PT-ACWO, tailored to correct pathological PTS, can substantially mitigate the risk of graft failure in ACLR and revision surgeries.[19,20] In our surgical protocol innovation, we conducted detailed preoperative CT scanning of the proximal tibia, followed by digital three-dimensional modeling based on CT data, which enabled computer-simulated osteotomies and the design of 3D-PSI. These models allow for exceptionally precise surgical planning.[21,22] The intraoperative use of 3D-PSI enables exact osteotomy and PTS correction, reducing the impact of surgical error during the cutting process. Accurate osteotomies significantly improve the integrity of the tibial posterior hinge and decrease the risk of damage to the neurovascular structures located posteriorly. Moreover, the application of 3D-PSI standardizes the PT-ACWO procedure, reducing the technical demands on the surgeon during osteotomy, as well as the associated surgical risks and complications.

Currently, although an increasing number of orthopedic surgeons are willing to attempt PT-ACWO in ACLR or revision surgeries, there is still uncertainty due to limited case numbers and the lack of long-term clinical follow-up results. Despite ongoing exploration, a consensus on the standard operative technique for PT-ACWO has not been established. Early studies[19,20] typically involved detaching and then reattaching the tibial tubercle after performing the wedge osteotomy. Although these studies reported favorable clinical follow-up outcomes, moving the tibial tubercle may pose risks affecting the patellar height and healing at the osteotomy site of the tibial tubercle. Osteotomy of the tibial tubercle can also restrict the intensity of early postoperative rehabilitation. Tilman Hees performed osteotomies distal to the tibial tubercle, and improvements in the proximal tibial osteotomy site further mitigated the potential risks associated with osteotomizing the tibial tubercle, having a lesser impact on patellofemoral kinematics.[23]They also emphasized the importance of preserving the integrity of the hinge post-osteotomy and suggested the use of angle-stable plate fixators for stabilization after the osteotomy. Drawing from the common pitfalls and preventative measures associated with closed-wedge osteotomy, we also made targeted improvements in our PT-ACWO approach. Moreover, compared to transverse osteotomy, the oblique osteotomy we employed offered clear advantages. The hinge point of the oblique osteotomy was further from the anterior opening on the tibia than in the transverse osteotomy, which significantly reduced the tension on the hinge point at the posterior tibia during the closure of the osteotomy gap, thus avoiding hinge point fractures. In our study, none of the five knees that underwent the oblique osteotomy experienced hinge point fractures. The oblique osteotomy increased the surface area of the osteotomy, which facilitated the fixation of the osteotomized surfaces post-operatively. The osteotomy gap of the oblique osteotomy angled posteriorly and superiorly, with a greater volume of cancellous bone beneficial for osseous healing at the osteotomy site in the later stages. After high tibial osteotomy, to ensure multiplanar stability at the osteotomy site, the use of multi-angle fixation screws was advantageous for early resumption of rehabilitative exercises.

Additionally, we experimented with a new fixation system—the OBS fixation system—which not only minimized the spatial conflicts between the osteotomy fixation and the revision tunnels for ACLR, but also allowed for the remolding of the internal fixation rod to better conform to the tibia. Moreover, the screw holes on the fixation rod were designed to be slidable, allowing for multi-directional and multi-angled fixation to meet diverse stabilization requirements. This approach yielded satisfactory clinical outcomes in our study subjects.

By the final follow-up, our study demonstrated satisfactory clinical outcomes for the combination of ACLR revision surgery and PT-ACWO. None of the cases in our study experienced recurrent knee instability or graft failure. D Dejour et al.[19] reported that the correction of the pathological PTS during secondary revision ACLR can improve knee stability and effectively prevent graft rupture. It was also suggested that the pathological PTS should be considered for correction at the time of the first ACLR revision to significantly reduce the risk of postoperative failure in patients. A retrospective evaluation of five cases involving second revision ACLR combined with proximal tibial closed-wedge osteotomy indicated that although correcting the PTS did not restore the function to pre-injury levels in patients with repeated ACL ruptures and pathological PTS, the overall clinical outcomes were satisfactory.[20] Our study also demonstrated that this technique indeed offers substantial benefits in improving knee function and stability without additional complications. Overall, we made certain improvements and trials based on previous studies, which present a surgical option worth considering for patients with ACLR graft failure and pathological PTS. Of course, satisfactory clinical outcomes cannot be achieved without strict control of surgical indications, meticulous preoperative planning, precise surgical technique, and standardized postoperative rehabilitation.

Our study also shared some of the weaknesses common to other research, such as a small sample size and an insufficiently long postoperative follow-up period. We did not perform a comparative study on the role of PT-ACWO in the revision of ACLR, nor were we able to assess the impact of different patient characteristics on the efficacy of 3D-PSI. Future studies with larger samples and longer follow-up periods are anticipated to better evaluate the clinical outcomes of this surgical approach.

5. Conclusion

In conclusion, the study highlights the importance of PTS on ACL strain and knee stability, noting that a PTS above 12° may cause increased strain. Our findings reveal that PT-ACWO effectively corrects PTS abnormalities and mitigates instability in ACLR patients, as shown in a 7-patient cohort with significant PTS reduction and preserved graft integrity over a 2-years follow-up. The use of 3D-PSI, in conjunction with traditional surgery, has proven beneficial for precise corrections and improved knee joint outcomes. Further studies with more participants are warranted to corroborate these findings and optimize surgical techniques.

Ethics

The procedures followed in our study were in accordance with the ethical standards of the Responsible Committee on human experimentation (institutional) and with the Helsinki Declaration of 1975, according to the revised version in 2013.

Declaration of competing interest

All authors declare that they have no potential conflicts of interest in this work.

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