Anterior Closing-Wedge High Tibial Slope-Correcting Osteotomy Using Patient-Specific Preoperative Planning Software for Failed Anterior Cruciate Ligament Reconstruction

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Abstract: Failure of anterior cruciate ligament reconstruction (ACLR) remains a challenging problem. Recently, the effect of increased posterior tibial slope has been identified as a risk factor for ACLR failure. In cases with increased posterior tibial slope, an anterior closing wedge, slope-correcting high tibial osteotomy can be used as a robust adjunct to revision ACLR. In this Technical Note, we demonstrate our preferred method for isolated sagittal plane correction following multiple failed ACLRs with an anterior closing-wedge high tibial osteotomy technique using 3-dimensional patient-specific instrumentation. Through correction of the angular deformity and restoration of the defined sagittal slope via the use of advanced 3-dimensional patient-specific instrumentation, this technique fosters an accurate, favorable mechanical environment to prevent recurrent instability of the knee joint.

Failed reconstruction of the anterior cruciate ligament (ACL) remains a challenging problem. Several factors, such as tunnel misplacement, inappropriate graft selection, and missed concomitant injuries, have been identified to contribute to failure after ACL reconstruction (ACLR).[1,2] Notwithstanding, the effect of increased posterior tibial slope (PTS) has recently surfaced as a risk factor for ACLR failure.[3] In cases of increased PTS, a high tibial osteotomy (HTO) using an anterior closing-wedge or medial opening-wedge technique has proven to be a robust supplemental treatment to revision ACLR.[4] Biomechanically, leveling of the tibial slope decreases strain on the ACL and redistributes weight-bearing forces toward the posterior compartment.[5] Survivorship of tibial slope−reducing osteotomies using an opening- or closing-wedge HTO technique for ACL deficiency or following ACLR failure has been reported as high as 95% at a minimum of 5 years' follow-up.[6]

Accurate correction of the sagittal deformity is essential in an anterior closing-wedge HTO to ensure proper restoration of the TS. Overcorrection can lead to increased stress on the posterior cruciate ligament, whereas undercorrection can lead to persistent ACL strain. While current techniques for preoperative HTO planning include primarily weight-bearing radiographs to calculate corrective coronal and sagittal plane angles, variable position during radiography and limited

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The authors report the following potential conflicts of interest or sources of funding: M.T.P. reports personal fees from Arthrex, Joint Surface Foundation, SLACK, and Arthrosurface, during the conduct of the study; and is an editorial and governing board member of AANA, American Academy of Orthopaedic Surgeons, American Orthopaedic Society for Sports Medicine, American Shoulder and Elbow Surgeons, International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine, the San Diego Shoulder Institute, and the Society of Military Orthopaedic Surgeons. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

Received May 4, 2022; accepted July 25, 2022.

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2212-6287/22606

https://doi.org/10.1016/j.eats.2022.07.015

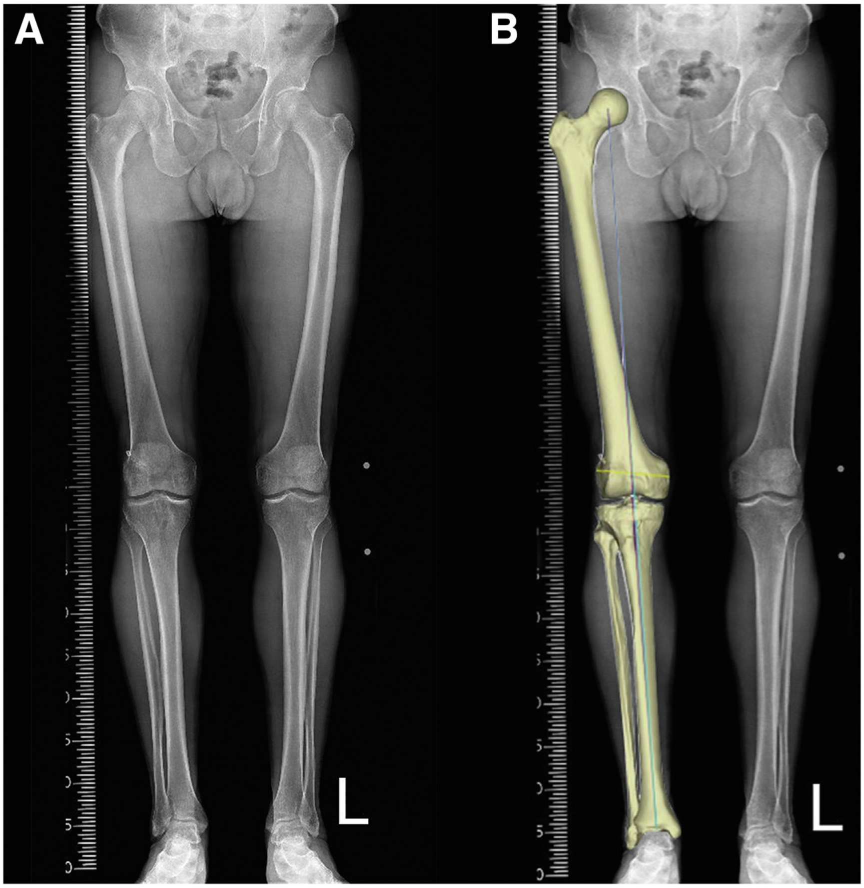

Fig 1. Preoperative planning images including both (A) a full-length anteroposterior (AP) radiograph and (B) a 3-dimensional computed tomography scan of the right lower limb (hip to ankle) that be adjusted to the full-length AP radiograph for obtaining an accurate anatomic topology of the knee joint.

2-dimensional views can lead to disparities between planned and actual correction.[7] Recent advancements in 3-dimensional, patient-specific instrumentation (3D PSI) have provided surgeons with a viable option for improving accuracy in preoperative planning and subsequent intraoperative reproducibility, with errors reported as low as 0.3° to 0.7°.[7]

The purpose of this Technical Note is to demonstrate our preferred method for isolated PTS correction following multiple failed ACLRs with an anterior closing-wedge HTO technique using 3D PSI. Through correction of the angular deformity and restoration of the defined sagittal slope via the use of advanced 3D PSI, this repair technique fosters an accurate, favorable mechanical environment to potentially improve longevity of the knee joint.

Surgical Technique (With Video Illustration)

The surgical technique is reviewed in Video 1.

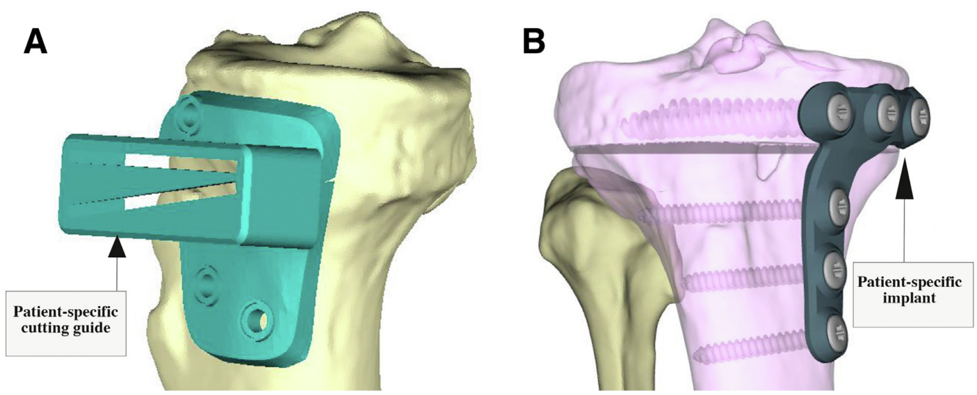

Fig 2. Patient-specific planning software using Bodycad Personalized Restoration Software displaying (A) patient-specific cutting guide and (B) patient-specific implant (BC Fine Osteotomy; Bodycad Laboratories Inc., Quebec, Canada).

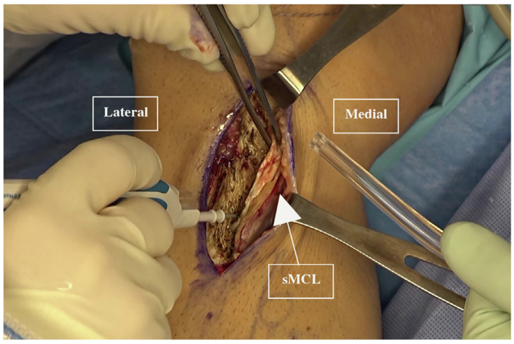

Fig 3. Intraoperative photograph of the right knee (supine position). Identification of the superficial medial collateral ligament (sMCL) of the right knee. The MCL sharply elevated from anterior to posterior, underneath the pes anserine, keeping intact the proximal and distal MCL insertions.

Preoperative Planning

Preoperative planning includes both a full-length anteroposterior radiograph and computed tomography scan of the lower limb (hip to ankle) to obtain an accurate anatomic topology of the knee joint (Fig 1). Both the patients' preoperative computed tomography scan and radiograph data are sent to the Bodycad Personalized Restoration Software (Bodycad Laboratories Inc., Quebec, Canada) for patient-specific preoperative planning of the desired sagittal correction. The patient-specific cutting guides and stainless-steel plate are 3D-printed and sent to the hospital for surgical implantation (BC Fine Osteotomy, Bodycad Laboratories Inc., Quebec, Canada). Thus, a patient-specific plate and cutting guide are used to get precise slope correction (Fig 2).

Patient Positioning

After an induction of general anesthesia, an examination under anesthesia is performed to evaluate knee range of motion as well as to assess knee stability in each direction. The patient is then placed in the supine

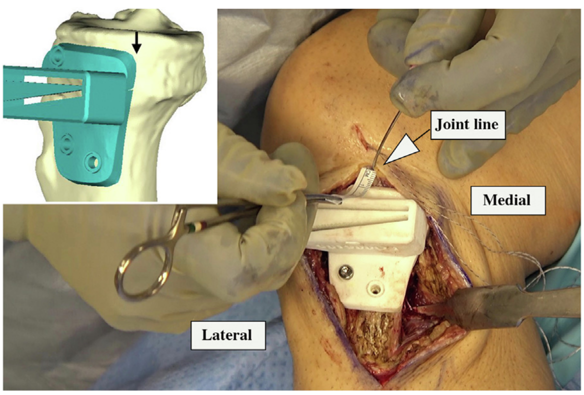

Fig 4. Intraoperative photograph of the right knee (supine position). Placement of the patient-specific cutting guide against the curvature of the medial tibial border of the right knee. The cutting guide demonstrates a perfect fit and is the distance from the planned joint line is rechecked.

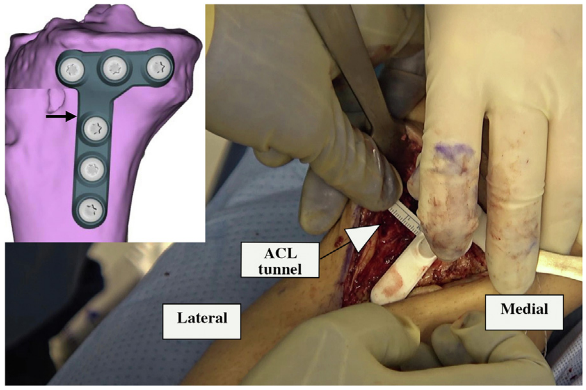

Fig 5. Intraoperative photograph of the right knee (supine position). Application of the predrill guide to the tibial bone surface of the right knee. The planned distance between the anterior cruciate ligament (ACL) tibial tunnel and the predrill guide is confirmed.

position. All bony prominences are well padded. After completion of patient positioning and examination under anesthesia, the knee is prepped and draped in a standard sterile fashion. A well-padded tourniquet is used and insufflated to 200 mm Hg during the case.

Diagnostic Arthroscopy and Arthroscopic Procedures

A diagnostic knee arthroscopy is performed using standard inferolateral and inferomedial portals. Synovitis and the ACL footprint are debrided. The lateral meniscal root repair is first addressed. The attachment site of the lateral meniscal root is identified and debrided using a combination of a curette, a shaver, and a high-speed bone cutting burr. The root tear is prepared with a rasp. Three high-strength meniscal luggage-tag sutures (FiberLinks sutures; Arthrex, Naples, FL) are passed with a meniscal suture passer (Scorpion suture passers; Arthrex) within the posterior root of lateral meniscus in a luggage-tag fashion. Next, a drill guide is set at 55° and placed intra-articular at the anatomic footprint of the

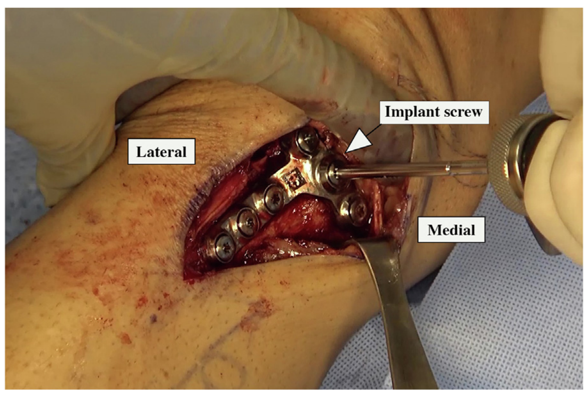

Fig 6. Intraoperative photograph of the right knee (supine position). Securement of the patient-specific plate against the bone surface of the right tibia with implant screws.

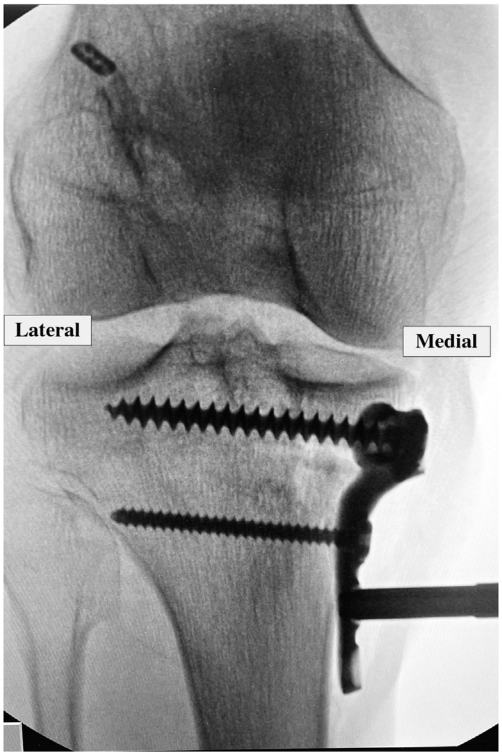

Fig 7. Fluoroscopic image at the operative theater, right knee (supine position). Fluoroscopy shows a well-positioned hardware and the completion of the osteotomy.

posterior lateral meniscal root and extra-articular on the tibia just medial to the expected ACL tibial tunnel. A transtibial tunnel is drilled at these sites using a canulated drill. Next, a passing suture is placed through the cannulated drill to shuttle the meniscal sutures through the tibial tunnel. Following this, the meniscal root sutures are secured with a 4.75-mm knotless anchor (SwiveLock anchors; Arthrex) on the tibia under arthroscopic visualization. Of note, the final drilling, passing, and fixation of sutures through the tibial tunnel is performed after the HTO is completed.

HTO Preparation

The patient-specific tibial 3D-printed bone model and fine osteotomy implants are prepared on the operative table (BC Fine Osteotomy, Bodycad Laboratories Inc., Quebec, Canada). The patient-specific cutting guide is then placed against the 3D-printed patient-specific bone model and its proximal border is marked with a pen. The distance from the cutting guide and the joint line is measured with a ruler. In addition, the bone model is marked and measured for the optimal plate position after osteotomy completion.

Next, a mid-medial skin incision is made. The superficial medial collateral ligament (MCL) is identified and sharply elevated from anterior to posterior, underneath the pes anserine, keeping intact the proximal and distal MCL insertions (Fig 3). In addition, the exposure is carried anteriorly to the medial aspect of the tibial tubercle and patellar tendon insertion. The knee is kept in a flexed position during exposure to decrease the tension of the posterior neurovascular structures and the MCL. The patellar tendon and the neurovascular structure are protected anteriorly and posteriorly, respectively, with blunt retractors. The bone surface is carefully preserved during exposure but cleared of all soft tissue to obtain a proper fit of the patient-specific cutting guide. Also, care is taken to ensure the exposure provides access to the joint line for assessment of proper guide placement. Then, the previous ACL tibial tunnel is identified, debrided, and drilled with a 10-mm acorn reamer to remove all debris from the tunnel.

Anterior Closing-Wedge HTO

The patient-specific cutting guide is then placed with a “perfect” fit to the curvature of the proximal medial tibial border. The position and distance of the cutting guide from the joint line is confirmed (Fig 4). Next, self-drilling and self-tapping screws are placed to fixate the cutting guide in position.

Following this, 1 of the 2 drill towers is assembled to the cutting guide by attaching it over the surgical slot. The proper drill bit that matches the tower and the planned cut is selected. The drill bit is gently advanced sequentially into each drill slot and stopped by the tower guide, typically working from anterior to posterior, precutting the bone before osteotomy completion with an osteotome. Once each slot of the first tower is drilled, the drill bit is removed, and the same sequence is performed for the second drill tower.

Next, the osteotomy is completed by carefully advancing an osteotome to determined depths based on the preoperative plan. A curette and rongeur are used to remove any remaining bone at the osteotomy site. The osteotomy is then gently closed by extension of the knee.

The plate drill guide is then affixed to the proximal medial tibia. To ensure proper position, the distance between the ACL tibial tunnel and the predrill guide is confirmed (Fig 5). A 3.2-mm drill bit is used to predrill for plate application. The patient-specific 3D-printed stainless-steel plate is placed and secured to the proximal medial tibia with screws (Fig 6).

Fluoroscopy is used to ensure completion of the osteotomy and appropriate hardware positioning (Fig 7). It is important to have the joint line parallel to the fluoroscopic beam when assessing these images. After the osteotomy completion and implant positioning are confirmed, all screws are final tightened.

Tibial Tunnel Bone Grafting (First-Stage Revision ACLR)

After the HTO is completed, the previous ACL tibial tunnel is filled with a combination of bone from the osteotomy site and allograft chips (JRF Ortho,

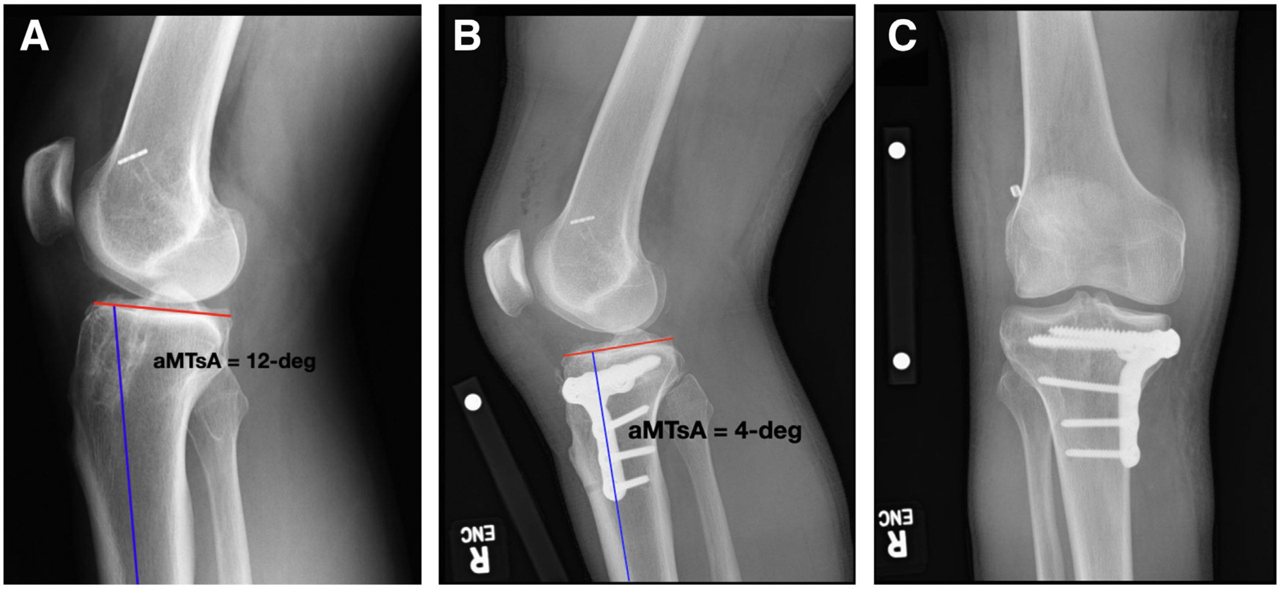

Fig 8. Radiographs of the right knee. (A) preoperative lateral right knee and postoperative (B) lateral and (C) anteroposterior radiographs demonstrating correction to the desired alignment of the posterior tibial slope was achieved. (aMTsA, anatomic medial tibial slope angle.)

Centennial, CO). At this point, the tourniquet is released, and all wounds are copiously irrigated. The MCL is first closed with No. 0 VICRYL (Ethicon, Somerville, NJ) suture. The pes anserine is also fully repaired with No. 0 VICRYL (Ethicon) suture. The surgical wound is then closed in layered fashion with No. 2-0 MONOCRYL (Ethicon) suture in the deep dermal layer, and a No. 3-0 MONOCRYL (Ethicon) subcuticular stitch. Next, a sterile dressing is applied.

Postoperative Rehabilitation

The patient is initially placed in a hinged knee brace for the first 6 weeks after surgery. Full range of motion is permitted as tolerated. The patient will be 10-pound touch down weight-bearing with crutches for 4 weeks since this is a closing wedge osteotomy. Postoperative knee radiographs are obtained to determine the PTS (Fig 8). The pearls and pitfalls of the described technique are listed in Table 1.

Table 1. The Pearls and Pitfalls of Anterior Closing-Wedge High Tibial Osteotomy Using Advanced Preoperative Planning Software

Pearls	Pitfalls
Preoperative planning with advanced imaging including a full-length AP radiograph and CT scan of lower limb (hip to ankle) is crucial	Inaccurate placement of patient-specific cutting guide or predrill guide may result in wrong sagittal or coronal alignment corrections
The MCL sharply elevated from anterior to posterior, underneath the pes anserine, to keep the proximal and distal MCL insertions intact.	MCL injury; patellar tendon injury
Ensure the exposure is large enough anteriorly and posteriorly for guide placement and accurate assessment of the joint line.	The patient-specific tibial 3D bone model and fine osteotomy implants may need a brief period of manufacturing
The patient-specific cutting guide was placed and perfectly fit to the medial border of the tibia in accordance with the distance from the joint line level as planned.	Inadequate exposure anteriorly, posteriorly, and/or to the joint line, resulting in improper cut guide positioning.
The distance between the ACL tibial tunnel and the predrill guide is confirmed as planned before placement	Removal of bone during exposure leads to alteration of anatomy and improper fit of the cutting guide.
Fluoroscopic images obtained parallel to the joint to ensure that the osteotomy was completed, and that the hardware was in a good position	
Care should be taken not to remove any bone during exposure before placement of the cutting guide, as its position is based on the CT-acquired bony anatomy.	

3D, 3-dimensional; ACL, anterior cruciate ligament; AP, anteroposterior, CT, computed tomography; MCL, medial collateral ligament.

Discussion

This Technical Note describes our technique for PTS correction following multiple failed ACLRs using an anterior closing-wedge HTO and advanced 3D PSI. Through correction of the angular deformity and restoration of the defined sagittal slope via the use of 3D PSI, this repair technique fosters a precise, favorable mechanical environment to prevent recurrent instability of the knee joint.

The anterior closing-wedge HTO for PTS correction has become an increasingly popular technique used to correct angular deformity and normalize joint forces of the knee.[5,8,9] However, recent implementation of advanced 3D PSI has further enhanced the novelty of this technique.[7] Accordingly, there exists a paucity of literature that investigates outcomes of these patients. In their biomechanical study of 10 cadaveric specimens with proximal tibial slope deformities, Donnez et al.[10] assessed the accuracy of 3D patient-specific cutting guides for opening-wedge HTO. The authors reported that the mean difference between planned and postopening-wedge HTO correction differed by only 0.2° (max 0.5°, SD 0.3°) in the frontal plane and −0.1° (max 0.8°, SD 0.5°) in the sagittal plane.[10] The clinical implications of Donnez et al.'s analysis were recently illustrated in a prospective cohort study by Chaouche et al.,[11] In which 100 patients with severe PTS who underwent an opening-wedge HTO using 3D patient-specific cutting guides reported a significant improvement in Knee injury and Osteoarthritis Outcome Score Pain (27 ± 25), symptoms (27 ± 28), and sport/rec (28 ± 38) ($P < .001$) at minimum 2-year follow-up. Together, these studies highlight that tibial slope−reducing osteotomies with the use of 3D PSI is an effective and safe procedure in patients who present with increased PTS. Nonetheless, additional studies with larger patient populations and longer-term follow-up, specifically using an anterior-closing wedge HTO technique, are needed to further investigate functional outcomes and to elucidate potential limitations of this procedure.

Recent literature has proven that increased PTS is a significant risk factor for ACL injury and graft failure after ACLR.[4,12] While slope reducing osteotomies in the sagittal plane have advanced in recent years, evidence of an optimal technique remains less delineated.[4] To our knowledge, few case series exist in which increased PTS was reduced using a closing-wedge HTO technique following ACL deficiency or ACLR failure.[4,8,9] Contrary to other techniques, ours uses an infratubercle approach in which the osteotomy begins just below the tibial tubercle, the hinge point is centered on the PCL insertion, and the osteotomy is fixed with an anteromedially positioned plate. We believe that this method, alternative to a supratubercle approach, is easier to be performed, less invasive, and offers improved plate fixation for earlier weight bearing.[4,13,14] In the setting of isolated severe PTS in which there is no significant coronal malalignment, whether a uniplanar slope decreasing osteotomy is more effective compared with a multiplanar correction remains more elusive.

In their retrospective cohort study, Weiler et al.[4] examined outcomes of 76 patients with a failed ACLR treated for severe PTS with either an anterior closing wedge or multiplanar medial opening wedge HTO technique. The authors reported that while there was a mild correlation between amount of sagittal correction and coronal alteration ($R = -0.29$, $P = .028$), mean PTS correction was significantly greater in patients who underwent solely sagittal corrections compared with combined coronal and sagittal procedures (8.1 ± 1.6° vs 6.4 ± 1.6°, $P = .0002$). Such findings encourage the use of an anterior opening-wedge osteotomy as a sole sagittal correcting procedure in the case of isolated severe PTS; however, additional, well-powered studies are necessary to further investigate the benefits of this technique.

In conclusion, this Technical Note highlights our technique for isolated PTS correction in the setting of multiple failed ACLRs using an anterior closing-wedge HTO technique and advanced 3D PSI. We believe that this uniplanar approach addresses sagittal malalignment without disruption of the coronal plane, is less invasive, and offers safer plate fixation for earlier weight bearing. In addition, implementation of 3D PSI ensures accurate correction of desired planar alignment to improve stability of the knee joint.

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