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Review

Posterior Tibial Slope-Modifying Osteotomies: Current Concepts in Biomechanics, Indications, Surgical Techniques and Outcomes

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ABSTRACT

The posterior tibial slope (PTS) is a key determinant of knee biomechanics, influencing anterior and posterior cruciate ligament (PCL) function, joint stability and load distribution. Abnormal PTS values predispose to instability and ligament reconstruction failures. This review aims to synthesize current evidence regarding the biomechanical, clinical, and surgical principles of PTS-modifying osteotomies, emphasizing their indications, techniques and outcomes. A comprehensive narrative review of the literature was conducted focusing on the definition, measurement methods, biomechanical implications, surgical approaches, and clinical results of PTS-reducing and PTS-increasing tibial osteotomies. Key data were extracted from biomechanical, radiologic, and clinical studies evaluating PTS correction and its effect on knee stability and success of ligamentous reconstruction. Measurement of PTS varies significantly among studies due to inconsistent radiological methods, i.e. radiograph versus magnetic resonance imaging or reference points and tibial axis definitions. PTS-reducing osteotomies effectively decrease anterior tibial translation, improving stability in ACL-deficient knees, while PTS-increasing procedures restore stability in PCL insufficiency and genu recurvatum deformities. Both techniques demonstrate substantial postoperative improvements in functional scores (Lysholm, IKDC, Tegner) with reported success rates up to 80–85%. Common complications include hinge fractures, patellar maltracking, and loss of correction, mitigated by accurate planning and fixation. PTS-modifying osteotomies represent valuable tools for managing ligamentous knee instability secondary to abnormal PTS. Optimal outcomes depend on precise radiologic assessment, appropriate surgical selection, and structured rehabilitation. Further longitudinal studies are warranted to determine their long-term effects on joint preservation and osteoarthritis progression.

Keywords: Anterior cruciate ligament, high tibial osteotomy, knee biomechanics, posterior cruciate ligament, posterior tibial slope, revision ligament reconstruction, slope-increasing osteotomy, slope-reducing osteotomy

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INTRODUCTION

The posterior tibial slope (PTS) plays a critical role in knee biomechanics, influencing both the stability and function of the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL).[1,2] Therefore, PTS-modifying osteotomies, either increasing or decreasing the slope, represent surgical techniques developed to correct knee instability related to abnormal PTS angles. PTS-increasing osteotomies are generally performed to correct posterior knee instability [3,4], especially in cases of PCL insufficiency, whereas PTS-decreasing osteotomies are applied to reduce anterior tibial translation (ATT) in ACL-deficient knees [5,6]. In this extensive review, both procedures are discussed in the context of their biomechanical role, clinical indications, various operative approaches, and outcomes.

The biomechanical importance of PTS has been well established. Increased PTS results in greater ATT under axial loading, thereby increasing strain on the ACL and contributing to both primary injury and graft failure.[7,8] Conversely, decreased PTS is associated with increased posterior tibial translation and greater mechanical demand on the posterior cruciate ligament, leading to posterior instability.[9] These alterations in sagittal alignment influence tibiofemoral contact mechanics, joint loading patterns, and ligament forces, underscoring the central role of PTS in knee stability and kinematics.[8,10] It is important to differentiate between two distinct clinical concepts related to PTS correction. In many cases, changes in PTS occur as a secondary consequence of high tibial osteotomy performed primarily for coronal plane deformities or medial compartment osteoarthritis. In contrast, the PTS-modifying osteotomies described in this review refer to procedures intentionally performed in the sagittal plane to correct abnormal PTS in the setting of ligamentous instability, particularly ACL or PCL deficiency.

This narrative review was conducted to summarize the current evidence regarding PTS-modifying osteotomies of the proximal tibia. A literature search was performed using PubMed, Scopus, and Web of Science databases to identify relevant publications related to PTS and slope-modifying osteotomy techniques.

The search strategy included combinations of the following keywords: "posterior tibial slope," "tibial slope correction," PTS-modifying osteotomy," "anterior closing wedge osteotomy," "posterior opening wedge osteotomy," "anterior opening wedge osteotomy," and "high tibial osteotomy." Eligible publications included clinical studies, biomechanical investigations, systematic reviews, and technical reports focusing on the biomechanics, indications, surgical techniques, complications, and clinical outcomes of PTS-modifying osteotomies. Articles published in English and considered relevant to the topic were reviewed. In addition, the reference lists of selected studies were manually screened to identify further relevant publications. The aim of this review was to synthesize the available literature and provide a comprehensive overview of the biomechanical principles, clinical indications, surgical techniques, and reported outcomes associated with PTS-modifying osteotomies.

Definition and Measurement of PTS

The literature on PTS measurement reveals inconsistencies, leading to discrepancies in reported PTS values. Some studies have evaluated either the lateral or medial PTS individually, while others have not distinguished between the two.[7,11,12] Additionally, differences in the chosen tibial length on radiographs significantly affect PTS measurements.[13,14] Variations in the measurement approach are noteworthy because medial and lateral plateau PTS values can differ within individuals.[15,16] Studies have shown that using a 10 cm tibial length often leads to an overestimation of PTS by an average of 3 degrees compared to the mechanical axis.[17]

Several researchers have used different tibial diaphyseal levels to define the anatomical axis.[5,18,19] Some findings suggest that using the anatomical axis of the proximal tibia provides the most accurate PTS measurement compared to the mechanical axis of the tibia.[20] The widely accepted PTS cutoff value of 12 degrees was established using landmarks located 5 and 15 cm distal to the tibial joint line. A recent consensus report on revision ACL reconstruction also supports this methodology.[21] Full-length lateral tibial radiographs measured along the tibial mechanical axis are considered the most accurate method for determining PTS. However, patient-specific anatomy, such as tibial bowing, may affect PTS measurements, potentially influencing surgical decision-making.[17,22,23]

Studies have adopted various techniques to determine the tibial axis, including the anterior cortical line[24], the posterior cortical line[25], or an intermediate line[26] (Fig. 1). The anterior cortical line tends to overestimate PTS, while posterior referencing underestimates it.[27] Accurate lateral radiographic views with minimal posterior femoral condyle overlap (ideally <6 mm) are essential for accurate PTS measurements.[28] Research suggests that aligning the distal femoral surfaces of both condyles has a more significant impact on accuracy than aligning the posterior condyles.[29]

Despite its relevance, the influence of tibial rotation on measurements, particularly axial rotation and lateral tilting, is often neglected.[16] MRI and computed tomography (CT) scans provide greater precision in distinguishing between medial and lateral PTS.[15,30] However, there is no established MRI protocol for determining the optimal tibial length for PTS measurements. MRI-based approaches typically focus

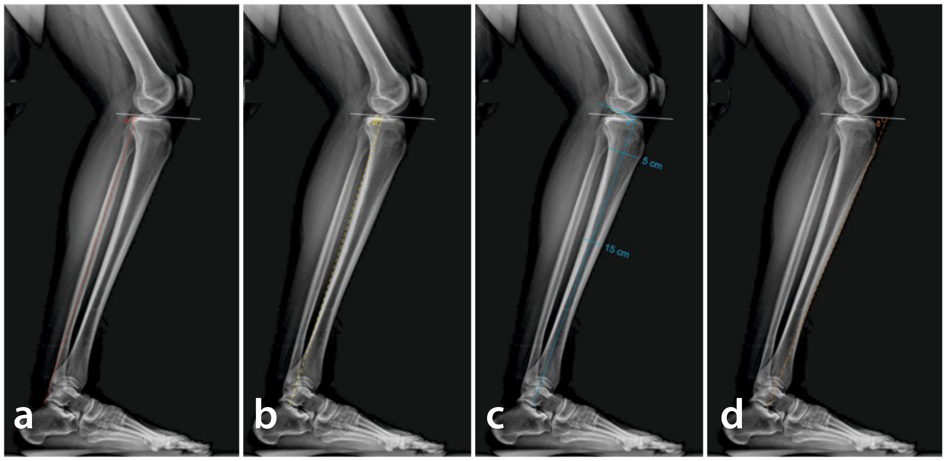

Figure 1. Commonly used reference methods for measuring posterior tibial slope (PTS) on a lateral knee radiograph. The figure illustrates four commonly described methods for determining the posterior tibial slope of the medial tibial plateau according to the tibial reference axis used. **(a)** Measurement based on the fibular diaphyseal axis, with PTS calculated as 90° – α. **(b)** Measurement based on the anterior tibial cortex axis, with PTS calculated as 90° – β. **(c)** Measurement based on the tibial proximal anatomic axis, the most commonly used reference method, with PTS calculated as 90° – γ. **(d)** Measurement based on the posterior tibial cortex axis, with PTS calculated as 90° – δ. Blue lines indicate the selected tibial reference axis and the tangent to the medial tibial plateau used for angle determination.

on the proximal tibia and may underestimate PTS. MRI-based approaches focusing on the proximal tibia may underestimate PTS, with studies reporting discrepancies of up to 4.9° compared to lateral knee radiographs.[31] For surgical decision-making, MRI- and CT-based PTS measurements should be avoided. Instead, lateral knee radiographs with at least 15 cm of the tibial diaphysis in view are preferred, utilizing the medial tibial plateau as a reference for PTS measurement. The tibial axis can be determined by placing two circles along the tibial diaphysis at 5 and 15 cm below the tibial plateau. [10] Currently, there is a lack of standardized guidelines for comparing PTS measurements across various imaging modalities, underscoring the importance of careful interpretation by surgeons and readers.[32]

Biomechanical Rationale

PTS-reducing osteotomies

The PTS significantly impacts ACL characteristics by means of its influence on ATT. A high PTS (≥12°) is an established risk factor for ACL injuries and subsequent reconstruction failure [28,33–35]. Increased PTS leads to larger ATT, placing excessive strain at the ACL, thereby increasing the risk of injury or graft failure.[33,36,37] PTS-reducing osteotomies aim at stabilizing the knee by reducing the PTS, hence decreasing the forces acting on the ACL, thereby improving ordinary knee biomechanics.[34,38]

PTS-increasing osteotomies

The dynamic effects of PCL deficiency also significantly impact the knee's long-term biomechanics, particularly in the patellofemoral and medial compartments. Posterior subluxation of the medial tibial plateau with knee flexion subjects the posterior horn of the medial meniscus to excessive forces, increasing contact pressures in the medial compartment by approximately 30%.[39–41] Additionally, the coupled anterior-posterior and rotational instability seen in PCL deficiency subjects the patellofemoral joint, especially the lateral patellar facet and inferior pole of the patella, to abnormally high contact pressures. These biomechanical consequences likely contribute to the accelerated osteoarthritic changes observed in these patients, further emphasizing the potential of medial opening wedge HTO to alter the progression of PCL-deficient knee conditions.[8,42] Besides ATT of 1.9±2.5 mm has been observed when axial compressive forces are applied.[8] In another study, increasing the axial compressive load from 134 to 200 N in a medial opening wedge HTO resulted in further ATT, corroborating the association between decreased PTS and increased risk of PCL reconstruction failure.[9,31]

Clinical Rationale

PTS-reducing osteotomies

Clinically, PTS-decreasing osteotomies are indicated for patients with ACL deficiency, particularly those with recurrent ACL injuries or failed ACL reconstructions associated with increased PTS.[33–35,43,44] Reducing the PTS to a neutral angle, usually between 4° and 6°, has been proven to enhance knee stability and reduce the risk of further ACL injuries.[13,45,46] Moreover, this technique may benefit patients suffering from meniscal injuries, patellofemoral instability, and early-onset osteoarthritis, all of which may be exacerbated by increased PTS.[10,33,37,47]

PTS-increasing osteotomies

Clinically, anti-recurvatum (PTS-Increasing) osteotomies are indicated for patients with pathological genu recurvatum deformities exceeding 15° and presenting with symptoms such as knee instability, anterior knee pain, and functional impairment. These deformities, often associated with either osseous alterations, soft tissue stretching, or a combination of both, can severely compromise joint stability, quadriceps function, and patellofemoral mechanics.[48,49] Correcting the deformity through an anterior opening wedge osteotomy has shown promising results, with studies reporting up to an 83% success rate in improving function and reducing pain, particularly when performed proximal to the tibial tuberosity.[50,51] This technique addresses hyperextension by increasing the PTS and improving knee biomechanics, making it a viable option for patients with debilitating recurvatum deformities or those experiencing anterior impingement symptoms due to hyperextension.[50–52]

Indications and Patient Selection

PTS-reducing osteotomies

PTS reducing osteotomies are primarily indicated in patients with an increased PTS, typically ≥12° on lateral radiographs.[35,50,53] Excessive PTS places greater mechanical stress on the ACL, particularly when ATT exceeds 10 mm.[13] Therefore, PTS-reducing osteotomies are most commonly considered in patients with recurrent anterior instability, especially in cases of failed or revision ACL reconstruction.[28,43] In addition, chronic meniscal injuries, particularly those involving the posterior horn of the medial meniscus, may coexist with increased PTS and contribute to abnormal knee biomechanics, further supporting the indication for PTS reducing osteotomy in appropriately selected patients. PTS should not be interpreted using a strict threshold value alone, as the risk of ACL failure increases progressively with increasing PTS and must be evaluated together with multiple patient-specific risk factors.[46]

PTS -increasing osteotomies

PTS -increasing osteotomies are generally indicated in patients with decreased PTS, typically <5° on lateral radiographs.[3] Reduced PTS may contribute to posterior knee instability and increased posterior tibial translation, particularly when posterior tibial translation exceeds 10 mm.[54] These procedures are therefore commonly considered in patients with symptomatic posterior instability, including those with previous PCL reconstruction failure. Posterior meniscal injuries associated with instability may also coexist with reduced PTS and further compromise knee biomechanics.

Patients with severe osteoarthritis, significant coronal plane deformities, or marked hyperextension deformities greater than 10° may not be suitable candidates for isolated PTS-modifying osteotomy and may require combined corrective procedures.[33]

Surgical Approaches

PTS-reducing osteotomies

Anterior closing wedge osteotomy

There are three primary techniques for handling the tibial tubercle during the procedure:

1. **Supra-tubercle Technique**: This approach potentially enhances healing due to the extensive surface area of cancellous bone available in the proximal tibia.[6] However, it poses challenges because of the thinness of the osteotomized segment, which increases the risk of inadvertent damage to the patellar tendon.[23]

2. **Infra-tubercle Technique**: This method is advantageous in maintaining the natural tension of the extensor mechanism, as it avoids direct manipulation. Hypothetically, it was assumed to carry a higher risk of nonunion, attributed to the distraction forces exerted by the patellar tendon on the proximal fragment and the relatively reduced vascular supply compared to the more proximal metaphyseal bone.[34,55] However, outcome studies have demonstrated rapid union following infratuberosity osteotomy.[56] A critical consideration lies in preoperative planning: prior work indicates that individualized planning is necessary for accurate osteotomy execution, rather than relying on the conventional "1 mm per degree" rule when performing a closing-wedge technique.[35]

3. **Tibial Tubercle Osteotomy (TTO) Technique: (Fig. 2):** This option is technically less demanding and permits adjustment of the tibial tubercle as needed for optimal alignment. However, it can limit early postoperative range of motion, potentially leading to knee stiffness, particularly when performed alongside ACL reconstruction.

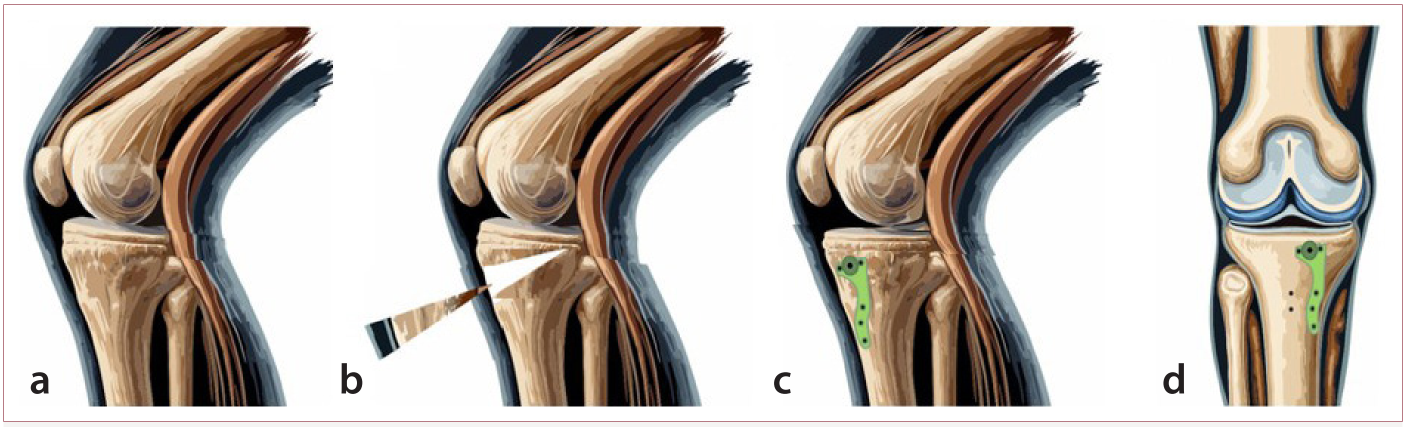

Figure 2. Surgical steps of anterior closing wedge proximal tibial osteotomy for posterior tibial slope reduction. **(a)** Lateral view of the proximal tibia demonstrating the planned osteotomy site. **(b)** Tibial tubercle osteotomy and resection of the anterior bony wedge. **(c)** Lateral view after completion of the anterior closing wedge osteotomy, showing reduction of the posterior tibial slope and stabilization with plate-and-screw fixation. **(d)** Anteroposterior view of the final construct demonstrating fixation of the osteotomy site.

Ultimately, each technique can achieve the desired correction, with the choice often depending on the surgeon's preference and the specific clinical scenario.[23]

Posterior opening wedge osteotomy

The posterior opening-wedge osteotomy (POWO) technique is designed to correct an excessive PTS, which can contribute to failed ACL reconstructions. This method involves exposing the posterior surface of the proximal tibia and inserting two K-wires anteroposteriorly as osteotomy guides, along with a mediolaterally inserted wire as a hinge blocker. The osteotomy is initiated posteriorly, advancing anteriorly with a single-bladed saw to open the osteotomy plane posteriorly with a gap spreader (Fig. 3). After the correction angle is achieved, fibular bone fragments are grafted into the opening to maintain stability, and a locking plate is applied for secure fixation. This technique is beneficial due to its minimally invasive approach, precise correction control, and ability to allow early rehabilitation, making it a preferred option for complex revision cases involving increased tibial PTS.[57]

PTS -Increasing Osteotomies

Anterior opening wedge osteotomy

There are two primary techniques for handling the tibial tubercle during the procedure described in the literature. However, because PTS-increasing procedures are rare, only limited case reports are available.

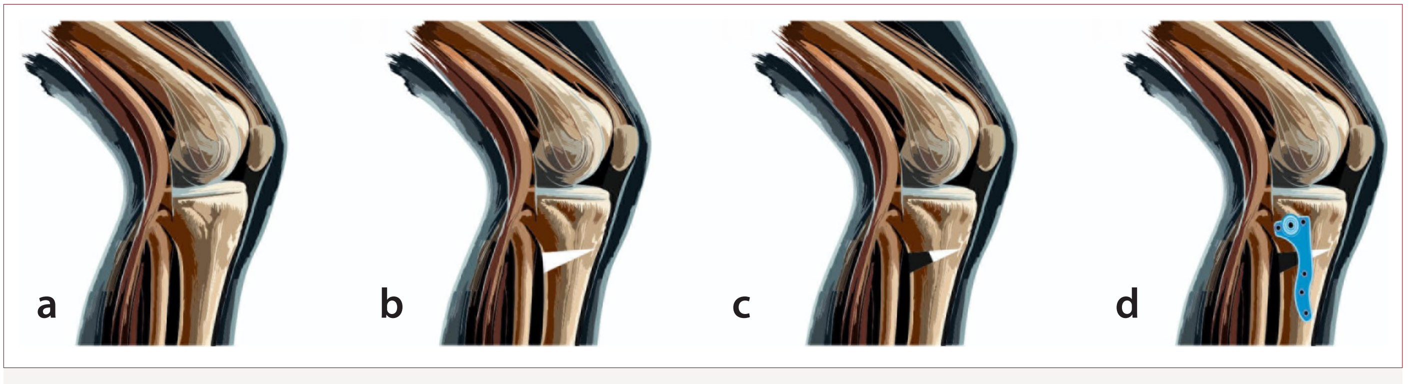

Figure 3. Surgical steps of posterior opening wedge proximal tibial osteotomy for posterior tibial slope increase. **(a)** The osteotomy is created beneath the first and second guide pins, progressing from posterior to anterior while preserving the anterior cortical hinge. **(b)** The osteotomy plane is gradually opened posteriorly using a gap spacer or laminar spreader. **(c)** Autologous fibular bone graft fragments are inserted into the osteotomy gap to maintain the correction. **(d)** Final stabilization is achieved with a locking plate and screws.

1. **Supra-tubercle Technique**: A plate and large Richards staple are used for fixation. This approach was reported in a patient with a 13-degree anterior tibial slope and failed PCL reconstruction.[20]

2. **Tibial Tubercle Osteotomy (TTO) Technique:** (**Fig. 4**) Another technique includes a tibial tubercle osteotomy (TTO) followed by an opening wedge high tibial osteotomy (HTO). This sequence helps avoid changes in patellar height during the correction.[58]

Postoperative Rehabilitation Protocols

Postoperative rehabilitation is crucial after both PTS-decreasing and PTS-increasing osteotomies. The following protocol represents a general rehabilitation framework commonly used after PTS-modifying osteotomies. In clinical practice, rehabilitation strategies may vary depending on the type of osteotomy performed, the fixation method used, the degree of correction, and the presence of concomitant ligament reconstruction procedures.[5,57,59]

Phase 1: Immediate Postoperative (0–3 weeks)

- Non-weight bearing with crutches
- Knee immobilization in full extension
- Early quadriceps activation and patellar mobilization

Phase 2: Early Rehabilitation (Weeks 4–6)

- Transition to partial weight bearing
- Gradual increase in range of motion, focusing on achieving full extension and flexion beyond 90°

Phase 3: Intermediate Rehabilitation (Weeks 7–12)

- Full weight bearing
- Strengthening exercises for quadriceps and hamstrings
- Balance and proprioceptive training

Phase 4: Advanced Rehabilitation (Weeks 12–24)

- Return to sport specific exercises and higher intensity activities
- Clearance for sports and high impact activities based on strength and neuromuscular control
- Pivoting and non-contact sports at 9 months, and pivoting and contact sports at 1 year postoperatively

Difficulties and Management

PTS modifying osteotomies are generally successful procedures; however, several complications may occur depending on the surgical technique, degree of correction, and fixation stability.

Anterior closing wedge osteotomy (ACW)

ACW procedures may be associated with loss of correction if fixation stability is insufficient or if premature weight bearing occurs during the early postoperative period.

Hinge fractures may also occur during large angular corrections when the cortical hinge is not adequately preserved. In addition, alterations in patellofemoral biomechanics may develop if patellar height changes occur following PTS reduction.[5,34,45,59–63]

Anterior opening wedge osteotomy (AOW)

AOW techniques may carry a risk of delayed union or nonunion due to the opening wedge gap and the need for stable fixation. Inadequate fixation stability or insufficient biological

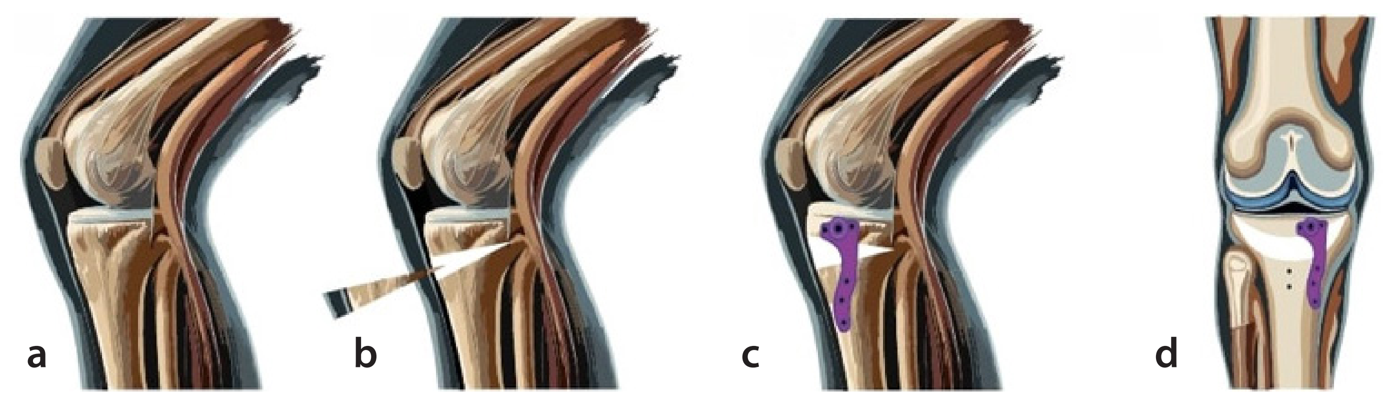

Figure 4. Schematic representation of anterior opening wedge proximal tibial osteotomy. **(a)** The intended osteotomy site is identified on the lateral aspect of the proximal tibia. **(b)** Tibial tubercle osteotomy is performed, and the osteotomy is opened anteriorly to achieve the planned correction. **(c)** Lateral view of the completed osteotomy with maintenance of the anterior opening wedge and stabilization using plate-and-screw fixation. **(d)** Anteroposterior view demonstrating the final fixation construct.

healing potential may contribute to delayed consolidation at the osteotomy site.[59]

Posterior opening wedge osteotomy (POWO)

POWO techniques require careful posterior exposure and may therefore carry a potential risk of neurovascular injury due to the close proximity of the popliteal neurovascular structures. In addition, PTS -reducing osteotomies may be associated with complications such as hinge fractures, infection, implant irritation or removal, and malcorrection.[64] Infection and hardware irritation are additional complications that may occur following PTS modifying osteotomies. Although the incidence of infection is generally lower compared with that associated with external fixation techniques, such as Ilizarov methods, implant-related irritation may occur and may require hardware removal.[58,59,61]

Clinical Results

Clinically, PTS -decreasing osteotomies are indicated for patients with ACL deficiencies, particularly those with recurrent ACL injuries or failed ACL reconstructions associated with increased posterior PTS.[33,34,43] Reducing the PTS to a more physiological range, typically between 4° and 6°, has been shown to improve knee stability and decrease the risk of further ACL injury or graft failure.[13,45] This approach may also benefit patients with associated meniscal pathology, patellofemoral instability, or early degenerative changes exacerbated by excessive PTS.[10,32,33] From a surgical decision-making perspective, PTS -reducing osteotomy may be considered in both primary and revision ACL reconstruction settings. In primary ACL reconstruction, PTS correction may be considered in carefully selected patients with markedly increased PTS and excessive ATT, particularly when additional risk factors such as chronic posterior horn meniscal injury are present.[65] Recent concepts such as the Avalanche classification emphasize that the indication for PTS -reducing osteotomy should be based on a multifactorial risk assessment rather than a single PTS threshold. [51] However, PTS -reducing osteotomy is more commonly performed in the revision ACL reconstruction setting, where excessive PTS has been identified as an important risk factor for graft failure and recurrent instability.[50,64] Correction of sagittal tibial alignment in these patients may reduce graft strain and improve the biomechanical environment for ligament reconstruction.

Both single-stage and staged surgical strategies have been described. In selected cases, PTS -reducing osteotomy can be performed simultaneously with revision ACL reconstruction, particularly when adequate tunnel positioning and fixation can be achieved during the same procedure.[65] Conversely, staged procedures may be preferred in complex revision situations, such as tunnel malposition, tunnel widening, or compromised bone stock, in which osteotomy is performed first to restore tibial alignment before definitive ligament reconstruction.[64]

Clinical studies have demonstrated that PTS -modifying osteotomies can lead to meaningful improvements in knee stability and functional outcomes. In patients undergoing PTS -reducing osteotomies, reductions in ATT and improvements in clinical scores such as the Lysholm score, Tegner activity scale, and IKDC score have been consistently reported.[5,44,62,63,66]

CONCLUSION

PTS modifying osteotomies represent essential surgical interventions for managing knee instability caused by abnormal PTS angles. These procedures whether aimed at increasing or decreasing the PTS address specific biomechanical and clinical challenges including ATT in ACL deficient knees and posterior instability in PCL deficient or genu recurvatum conditions. Precise measurements of PTS using standardized imaging techniques careful patient selection and tailored surgical planning are critical for optimizing outcomes. Biomechanical evidence underscores the profound impact of PTS on knee joint forces and ligament stability, making PTS modification a powerful tool for restoring normal knee biomechanics. Short- and mid-term results demonstrate significant improvements in instability, functional scores, knee stability, and patient satisfaction, highlighting the efficacy of these procedures. However, complications such as hinge fractures patellofemoral issues and loss of correction emphasize the need for meticulous surgical technique and robust postoperative rehabilitation protocols.

DECLARATIONS

EEthics Committee Approval: This is a review, and therefore, ethics committee approval was not required in accordance with institutional policies.

Informed Consent: Informed consent was not deemed necessary for this study.

Conflict of Interest: The authors declared no conflict of interest.

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ABBREVIATIONS

ACL: Anterior Cruciate Ligament

ACW: Anterior Closing Wedge Osteotomy

AOW: Anterior Opening Wedge Osteotomy

AP: Anteroposterior

ATT: Anterior Tibial Translation

CT: Computed Tomography

HTO: High Tibial Osteotomy

IKDC: International Knee Documentation Committee

MRI: Magnetic Resonance Imaging

PCL: Posterior Cruciate Ligament

POWO: Posterior Opening Wedge Osteotomy

PTS: Posterior Tibial Slope

TTO: Tibial Tubercle Osteotomy

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