State of the Art Review

Around-the-knee osteotomies part II: Surgical indications, techniques and outcomes – State of the art

Ariana Lotta a, Michael G. James a, Janina Kaarre a,d, Svenja Höger a,e, M. Enes Kayaalp a,b, Matthieu Ollivier f, Al Getgood g,h,i, Jonathan D. Hughesa, Volker Musahl a,*

a Department of Orthopaedic Surgery, UPMC Freddie Fu Sports Center, University of Pittsburgh, Pittsburgh, PA, USA
b Department of Orthopaedics and Traumatology, Istanbul Kartal Training and Research Hospital, Istanbul, Turkey
c Department of Orthopaedics, Institute of Clinical Sciences, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden
d Sahlgrenska Sports Medicine Center, Gothenburg, Sweden
e Department of Sports Orthopaedics, Klinikum Rechts der Isar, Technical University of Munich, Munich, Germany
f Aix Marseille Univ, CNRS, IEM, Inst Movement Sci, Marseille, France
g Kennedy Sport Medicine Clinic, University of Western Ontario, London, Ontario, Canada
h Lawson Health Research Institute, London, Ontario, Canada
i London Health Sciences Centre, London, Ontario, Canada

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ABSTRACT

Recent advances in surgical techniques and planning for knee-based osteotomies have led to improvements in addressing lower extremity malalignment. Part I of this review presented the biomechanical and clinical rationale of osteotomies, emphasizing the importance of osteotomies for restoring normal knee kinematics. In Part 2 of this review, indications, surgical technique and outcomes of osteotomies to correct coronal, sagittal and axial plane deformities will be examined. Traditional high tibial and distal femoral osteotomies will be discussed in addition to more recent advanced techniques including biplanar corrections and double-level osteotomies, as well as slope-correcting osteotomies. Patient-specific instrumentation and its use in more complex corrections will also be addressed.

INTRODUCTION

Knee-based osteotomies have traditionally been performed to address malalignment of the lower extremity. Abnormalities in coronal and sagittal alignment can lead to abnormal weight distribution and altered biomechanics, ultimately resulting in pain, knee instability and increased risk of injuries such as ligament tears and accelerated joint degeneration [1]. The objective of this review is to provide insights into evidence-based approaches for effectively managing both coronal, sagittal and axial knee deformity. Furthermore, this review will demonstrate the importance of identifying and addressing malalignment issues in clinical practice in addition to illustrating how a proper assessment can lead to improved functional outcomes and enhanced patient outcomes [2–4].

DEFORIENTATION ANALYSIS

Deforterioration of the lower extremity begins with an assessment of the patient’s coronal, sagittal and axial alignment. Evaluation of alignment is discussed in detail in Part I of this review series. Coronal alignment is typically evaluated using full-length, hip-to-ankle weight-bearing alignment radiographs. The mechanical axis femur (MAF) and tibia (MAT) are established with the angle formed between the MAF and MAT referred to as the mechanical tibiofemoral angle (mTFA). An angle of 0–3 degrees of valgus is indicative of neutral alignment. The site of deformity in patients with coronal malalignment can be determined by measuring the proximal tibial and distal femoral angles (mMPTA and mLDFA) are the angles between the respective joint line
and the corresponding mechanical axis with normal values ranging between 85 and 90°. Preoperative planning is imperative as recent studies have demonstrated that varus malalignment is not always the result of tibial deformity and similarly valgus deformity is not always femoral-based [5,6]. As discussed in Part I, osteotomies performed outside of the area of deformity can lead to joint line obliquity (JLO), which is defined as the angle between a line tangential to the tibial plateau and the ground line (Fig. 1).

The joint line convergence angle (JLCA) should also be measured as it approximates soft tissue tendon and intraarticular deformity. The JLCA is measured by the angle between lines tangential to the distal femoral condyles and the tibial plateau and is typically parallel in normal knees (0–2°). Calculation of JLCA is necessary as those patients with high JLCA can experience overcorrection after an osteotomy (particularly HTO) if the JLCA is not factored into the correction [5]. (Fig. 1) In addition to coronal alignment, sagittal alignment of the knee as represented by the posterior tibial slope (PTS) should be evaluated using lateral radiographs of the proximal tibia or ideally a full-length tibial radiograph with normal values ranging between 6 and 11° [7].

CORONAL MALALIGNMENT

Valgus-producing high tibial osteotomy

Given the many biomechanical consequences that varus alignment has on the knee, valgus-producing high tibial osteotomy (HTO) plays a role in managing multiple pathologies. For patients with varus alignment, deformity analysis must be performed to determine the location of the deformity. As varus deformity is most associated with tibial deformity, a tibial-based osteotomy is most commonly performed. Indications include medial compartment osteoarthritis, chronic ligamentous instability, meniscal deficiency and focal medial compartment cartilage defects.

Surgical indications

The main goal of valgus-producing HTOs is to unload the medial compartment in the setting of substantial metaphyseal deformity. By unloading the compartment, the osteotomy procedure can reduce pain, enable a return to work/recreational sports, stabilize the joint and delay the onset or progression of osteoarthritis. Isolated medial compartment osteoarthritis in patients less than 60 years old with full range of motion (ROM) is the most common indication for an HTO; however, additional surgical indications include varus alignment with medial compartment pathologies, chronic lateral ligamentous instability, failed anterior cruciate ligament reconstruction (ACL-R) in the setting of excessive PTS, varus deformity or combined deformity, and posterior cruciate ligament (PCL)/posterolateral corner instability (PLC) [8–11]. However, limited information exists regarding whether correcting varus malalignment in the setting of primary ACL-R decreases the rate of failure and the need for revision ACL-R [12]. While there is ample evidence suggesting that varus alignment leads to increased stress on the ACL graft, there are not enough comparative studies to demonstrate the need for valgus-producing HTO in the primary ACL-R reconstruction setting [13–17].

Valgus-producing HTOs are often performed in the context of medial meniscal or medial compartment cartilage restorative procedures. In joint preservation cases, correction of even subtle varus malalignment is imperative to decrease the stress on the reconstructed medial compartment. Lastly, several relative contraindications for valgus-producing HTO have been described including patients with patellofemoral or tri-compartmental arthritis, severe medial compartment osteoarthritis (Kellgren-Lawrence grade IV), limited knee ROM such as flexion contracture >10° and total arc of motion <120°, and inflammatory arthritis [18].

Surgical technique

When performing valgus-producing osteotomies, the present varus deformity should be corrected at the site of the deformity (tibia, femur, or intra-articular). Traditionally, the primary cause of knee varus deformity has been attributed to the tibia. Thus, the two most widely practised techniques for correcting varus malalignment around the knee are medial opening wedge (MOW) and lateral closing wedge (LCW) HTOs. While each approach comes with distinct advantages and disadvantages, both methods have been shown to be effective in relieving stress on the medial compartment by altering the mechanical axis of the lower limb [19].

Medial opening wedge (MOW) HTO. As illustrated in Table 1, there are several advantages to performing a MOW technique. This includes an often faster and higher precision procedure with the ability to preserve bone stock proximal to the tibial tubercle. However, disadvantages include the need for bone graft in the setting of larger corrections. When performing an HTO, pre-operative and planned post-correction JLO
should be assessed. If a planned single-level tibia osteotomy results in significant JLO \((>4/14)\), a double-level osteotomy (DLO) in which an osteotomy is performed above and below the knee joint should be considered. Second, assessing leg length discrepancy (LLD) is imperative, as MOW-HTO will increase leg length compared to LCW-HTO; however, this may vary based on the degree of correction needed [20].

The patellofemoral joint position is important to consider, as MOW-HTO has been shown to reduce patella height by 7% and alter patella tilt, particularly in corrections exceeding 15\(^\circ\) [21]. Alternatively, a biplanar infra tubercle osteotomy cut can be considered, as this is less likely to disrupt the length-tension relationship of the extensor mechanism [22].

### Lateral Closing Wedge (LCW) HTO

While surgeon comfort and familiarity with each technique is often the deciding factor between MOW-HTO and LCW-HTO, there are several advantages to LCW-HTO that may lead a LCW-HTO to be preferred. The major advantage of the LCW-HTO is the direct bone contact, which is thought to improve healing and stability of the construct. As referred to previously, LCW-HTO has not been shown to significantly alter patella height or tilt, so if there is pre-existing patella baja and/or significant patella tilt, LCW-HTO may be preferred. In addition, when analysing leg length discrepancy, in cases where the operative leg is already longer and requires substantial correction, the consideration of an LCW-HTO or a DLO instead of a MOW-HTO may be warranted.

However, for many surgeons, disrupting the proximal tibiofibular joint and dissecting around the peroneal nerve, as well as the need to make multiple precise cuts, makes LCW-HTO a less appealing option. In the setting of larger corrections (over 10 mm), a proximal fibula osteotomy is necessary to close the osteotomy. Caution must be taken to preserve the lateral collateral ligament when the proximal fibula osteotomy is performed [23]. Nevertheless, LCW-HTO remains a valuable option, especially in cases of significant leg length asymmetry or in cases with a high likelihood of non-union such as in smokers.

### Technical considerations

#### Surgical planning/degree of correction
Planning for MOW-HTO is typically performed using the Miniaci method and can be performed manually or with the assistance of digital planning software. The first step is to draw the Mikulicz line which is defined as the line starting from the centre of the femoral head to the centre of the talus [24]. Second, the desired post-operative weight-bearing point and hinge point are defined

### Table 1
Advantages and disadvantages of opening versus closing wedge HTO.

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<th>Opening Wedge HTO</th>
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<td>Advantages</td>
<td>Faster surgery</td>
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<td>Bone stock preserved:</td>
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<td>easier subsequent TKAs</td>
<td>Autologous bone/bone healing</td>
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<td>Disadvantages</td>
<td>Bone graft in the case of larger corrections</td>
<td>Longer surgery</td>
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<td>Risk of saphenous nerve injury</td>
<td>Lower precision</td>
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<td>Risk of patella baja</td>
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ACL-R = anterior cruciate ligament reconstruction; HTO = high tibial osteotomy; TKA = total knee arthroplasty.

[Fig. 2. Planning for a medial opening wedge high tibial osteotomy (Image a) The Mikulicz line (A) defined as the line starting from the centre of the femoral head to the centre of the talus is drawn, and a line from the centre of the femoral head through the desired weight-bearing point on the tibia (B) is drawn. (Image b) The hinge point is defined in the lateral proximal tibia at the level of the fibular head. A line is drawn (C) from the hinge point to the end of Line B at the level of the ankle and a similar line is drawn (D) from the hinge point to the current centre of the talus. The angle formed between lines C and D is the desired angle of correction \((\alpha)\). (Image c) This angle \(\alpha\) forms the correction angle for the medial opening wedge osteotomy.]
The hinge point is identified at the top of the fibular head in the lateral proximal tibial metaphysis. The angle is then drawn between a line connecting the initial position of the ankle to the hinge point and a line connecting the future position of the ankle to the hinge point. This angle will be the desired correction angle (Fig. 2). A similar method can be used to determine the correction for a LCO-HTO; however, the hinge point instead will be at the medial proximal tibia approximately 2 cm distal to the joint line and about 4–6 mm from the medial cortex [25].

Historically, valgus-producing HTOs were planned to correct to Fujisawa’s point (62.5% across the tibial plateau) [26]. However, there is emerging evidence that the degree of correction should depend on several factors, such as grade of osteoarthritis, ligamentous instability and alignment of the contralateral limb [26,27]. In general, the greater the degree of osteoarthritis, ligamentous instability and contralateral knee valgus, the more substantial the correction should be (i.e. 60–65%). Conversely, in a meniscal transplant or cartilage restoration procedure with minimal osteoarthritis and contralateral knee varus, the correction may only need to be 50–55%. The lateral tibial spine has been used as a simple and reproducible bony landmark when planning for valgus-producing osteotomies with the 55% correction point supported in recent consensus statements [28,29].

Bone graft. With the continued evolution of plating technology, the necessity of bone grafting in MOW-HTO is now somewhat controversial. For instance, a recent meta-analysis of 25 studies showed no difference in delayed union, non-union and correction loss between allograft, synthetic bone graft and no bone graft [30]. In our experience, the necessity of bone grafts should be evaluated on a case-by-case basis. The authors’ indication for a tibial allograft wedge is > 8 mm correction, as we believe this improves homeostasis and potentially osteotomy union and outcomes [31].

Hinge fractures. Hinge fractures are a known complication in valgus-producing HTOs, but steps can be taken to mitigate the occurrence and/or severity (Fig. 3). In the case of MOW-HTO, ensuring the osteotomy cut stops 5–10 mm from the lateral margin at the level of the upper third margin of the tibiofibular joint helps to decrease the rate and severity of hinge fractures [32]. More recently, the addition of a K-wire just medial and parallel to the lateral tibial cortex has been shown to increase the maximal load to breakage up to 880% [33]. The location of this wire is depicted in Fig. 3b. Hinge fractures are more likely to occur with larger corrections, particularly when gaps reach and exceed 11 mm [34]. As many hinge fractures can occur when the osteotomy gap is being opened, particularly in large corrections, the osteotomy gap should be opened slowly intraoperatively with stacked osteotomes or an opening device to minimize the risk of a hinge fracture.

Outcomes. Significant improvement in Lysholm and Tegner activity scores can be achieved with both MOW-HTO and LCW-HTO. The long-term viability of valgus-producing HTO is noteworthy, with survival rates of the native knee joint between 90 and 97% at 10 years for both MOW-HTO and LCW-HTO [4,35,36]. Nevertheless, the literature presents varying outcomes, mainly influenced by demographics and indications for valgus-producing HTO. A recent study demonstrated that patients undergoing LCW-HTO had a 22% rate of conversion to TKA at 6 years, while patients undergoing MOW-HTO had an 8% rate of conversion to TKA at 6 years [37]. Regarding return to work, a recent systematic review showed 84.5% of patients returned to work following...
valgus-producing HTO, with 65% returning to the same level [38]. Similarly, favourable outcomes were observed for returning to sport, with 87% of patients returning to sport and 78% at the same level. However, the prognosis for competitive athletes is more guarded, as this same systematic review reported that only 54% returned to “elite-level competition.” (38) Thus, there is ongoing debate about the role of valgus-producing HTOs in high-level athletes underscoring the need for further studies to provide clearer insights.

**Varus-producing distal femoral osteotomy**

The varus-producing distal femoral osteotomy (DFO) is often performed in the setting of symptomatic isolated lateral compartment osteoarthritis, lateral meniscus deficiency, patellofemoral instability, and/or persistent medial collateral ligament insufficiency. For patients with lateral compartment osteoarthritis and valgus alignment, deformity analysis must be performed to determine the location of the deformity. As valgus deformity is most associated with femoral deformity, a femoral-based osteotomy is most commonly performed. The distal femoral valgus osteotomy can be performed through either a medial closing wedge (MCW–DFO) or through a lateral opening wedge (LOW–DFO) approach, both of which will be discussed in this section.

**Surgical indications**

The most common indication for a varus-producing DFO is isolated symptomatic mild to moderate lateral compartment osteoarthritis with substantial metaphyseal deformity. However, it is also often performed in the context of other knee preservation procedures including cartilage procedures and meniscal allograft transplantations. In combined knee preservation cases, the correction of even minor valgus malalignment can effectively reduce the load on the lateral compartment and offload the meniscal or cartilage transplant [27]. Varus-producing DFOs are also often performed for patients with valgus alignment in the setting of patellar instability. Both valgus knee deformity and increased femoral anteversion have been shown to be risk factors for patellar instability [39]. It is essential to evaluate risk factors in patients with patellar instability, as isolated medial patellofemoral ligament (MPFL) reconstruction may be unsuccessful if knee malalignment is not addressed. Consequently, a varus-producing DFO or a derotational distal femoral osteotomy (DFO) may be indicated in patients with patellar instability and knee malalignment. Rotational osteotomies are discussed in further detail in a subsequent subsection of this review. Finally, while rare, a varus-producing DFO can be performed for medial collateral ligament (MCL) insufficiency. A valgus deformity results in an increased abduction moment, which consequently leads to greater tension on the medial and posteromedial structures [40]. However, varus-producing DFO for MCL insufficiency is very infrequent and existing literature on this topic is limited.

Relative contraindications to varus-producing DFO include pronounced valgus deformity accompanied by tibial subluxation, substantial knee instability, tricompartmental osteoarthritis and flexion contracture >15° [41,42]. Conversely, relative contraindications encompass severe patellofemoral osteoarthritis, rheumatoid arthritis, age over 65 years, substantial bone loss within the lateral compartment and a history of knee septic arthritis [27].

Lastly, while rare, valgus malalignment can also be corrected using a high tibial osteotomy, with both lateral opening and medial closing techniques described [43–45]. One recent study described a lateral opening wedge technique in which a fibular osteotomy is not required with no reported peroneal nerve injuries [44]. In addition, performing a varus-producing osteotomy through the proximal tibia offloads the joint throughout the flexion arc, while performing a varus-producing osteotomy through the distal femur mostly offloads during extension [46]. It is imperative when performing HTO for valgus deformity that JLO is avoided [43].

**Surgical techniques**

MCW and LOW techniques can be performed for distal femoral osteotomies. While the desired osteotomy point varies based on surgeon and indication, the aim of a varus-producing DFO is typically to move the load-bearing point within the 48%–50% segment of the tibial plateau width, measured from the medial to the lateral side [47]. Surgical planning for DFO can be performed using similar methods to those described previously for HTO. The first step is to draw the Mikulicz line which is defined as the line starting from the centre of the femoral head to the centre of the talus. Second, the desired post-operative weight-bearing point and hinge point are defined. The hinge point for the MCW–DFO should be approximately 5 mm from the lateral cortical bone to ensure that there is enough of a lateral hinge. The angle is then defined between a line connecting the centre of the femoral head to the hinge point and a line connecting the future position of the centre of the femoral head to the hinge point. This angle will be the desired correction angle (Fig. 4). A similar method can be used to determine the correction for a LOW–DFO; however, the hinge point will instead be near the adductor tubercle on the medial femur while preserving a 1 cm medial hinge. [43] While both MCW–DFO and LOW–DFO techniques have demonstrated effectiveness in reducing stress on the lateral compartment by shifting the mechanical axis medially, there are various factors elucidated below that can guide the decision to favour one technique over the other [48].

The MCW–DFO technique involves correcting the mechanical axis by removing a wedge-shaped bone block from the medial distal femur and is typically secured using plate fixation. Direct bone contact facilitates a more expedited bone healing process and the medial approach typically reduces soft tissue irritation [47]. Although MCW–DFO are thought to have a lower non-union or malunion rate compared to LOW–DFO, there is currently no evidence for reported radiographic correction or healing when comparing MCW–DFO and LOW–DFO [48]. A biplanar cut can also be performed and it is typically made in an ascending fashion on the femur which assists both with rotational stability of the osteotomy and healing (Fig. 5). In addition, there is no significant effect on leg lengths with either technique, MCW- or LOW–DFO. However, many surgeons regard the medial approach as more technically challenging [49].

In contrast, the LOW–DFO shifts the mechanical axis by placing a bone cut on the lateral distal femur while preserving the medial cortex, followed by a gradual widening of the lateral cortex [50]. One advantage of an LOW–DFO is the potential for a more accurate correction [48]. However, there is a higher risk of hardware irritation given the superficial anatomy of the lateral femur and slower time to union [47].

**Outcomes**

Similar to valgus-producing HTOs, published ten-year survivorship rates for varus-producing DFOs range from 65 to 90% [27,51]. Two early studies on varus-producing DFOs reported good or excellent outcomes for 71–83% of patients treated with a varus-producing DFO for valgus knee alignment [52,53]. However, in a more recent study that investigated the results of 30 patients who underwent a varus-producing DFO, there was 10-year survival rate of 87% when considering conversion to total knee arthroplasty (TKA) as the endpoint [41].

Data on combined procedures of DFO and cartilage restoration and/or meniscus transplantation are still limited. One recent study reported on outcomes of patients undergoing DFO and osteochondral allograft transplantation, citing an 89% survival rate at 10 years. However, survival rates sharply decreased after 10 years with a 20-year survival rate of 24% [54]. Another similar study cited a 92% 5-year survival rate for patients undergoing DFO with concomitant osteochondral allograft transplantation or meniscus allograft. The mean International Knee Documentation Committee (IKDC) score of this cohort increased to 62 from 36 pre-operatively [55].
Complications

Significant disparities exist in the literature regarding the reported complication rate after DFO, ranging from 0% to 63% [48,53,56,57]. The complications reported include nonunion/delayed union, loss of correction, stiffness, hardware discomfort and infection [26,47]. A systematic review reported rates of 8% and 23%, respectively, for hardware removal after MCW- and LOW-DFO [48]. The higher rate of hardware removal in patients who underwent LOW-DFO may be due to iliotibial band irritation. As discussed previously, while DFOs have successful short-term outcomes, failure rates (defined as conversion to TKA) increase significantly after a decade post-procedure. One recent study reported survival rates of 89.9% at 10 years, 78.9% at 15 years and 21.5% at 20 years [58].

Similarly, another study reported a 10-year survival rate of 82%, dropping to 45% at 15 years follow-up. After conversion to TKA, pain and functional scores improved, but not to the same level as a primary TKA [57]. Additionally, performing TKA in a patient with a prior DFO was notably technically more complex than performing primary TKA [59].

Double level osteotomy (DLO)

DLOs are osteotomies that are performed above and below the knee joint. DLOs are typically performed to correct biaxial deformity, which are deformities localized to both the femur and tibia [29,60,61]. For patients with a varus deformity, while there are no absolute indications, planned correction of the osteotomy by more than 15 mm or planned JLO of more than 4° are often indications for DLOs (Fig. 7). As highlighted in the first section of this review, while varus malalignment has historically been considered a femur-based deformity and valgus malalignment a tibia-based deformity, few cases have isolated tibial or femoral deformity [5]. For example, when analysing JLO after osteotomy simulation for patients with varus deformity, a recent study found that for anatomic correction (MPTA < 90°), DLO was necessary in 63% of patients [6]. However, when slight overcorrection was accepted (MPTA < 95°), 33% of patients required a DLO [6]. The technique for performing DLOs is similar to that of each respective single-level osteotomy as described in the prior sections. However, a decision must be made with respect to the order of osteotomy performed. Typically, the DFO is performed first followed by the HTO [62]. One of the advantages of performing DLOs is a decreased rate of hinge fractures, as smaller corrections can be performed on both the femur and tibia [63]. Patients who underwent DLO for larger corrections of varus deformity have been shown to have less
intra-operative hinge fractures, less post-operative JLO and slightly improved patient-reported outcomes and patient satisfaction scores compared to those who underwent isolated MOW-HTO [63]. There is a paucity of literature demonstrating differences in Knee Injury and Osteoarthritis Outcome Scores (KOOS) or return to sport/work rates for patients with DLOs compared to those who undergo isolated MOW-HTO. Results of patients after DLO for valgus alignment have demonstrated improvement in all KOOS subscores with a mean return to sport rate of 5 months [64].

SAGITTAL MALALIGNMENT

The impact of tibial slope on knee instability in the setting of ACL and PCL injuries has been increasingly studied. This section will focus on slope-correcting tibial osteotomies (anterior closing and anterior opening wedge techniques) that can be used to adjust sagittal alignment.

Anterior closing wedge osteotomy

Failure of ACL-R continues to be a pervasive issue despite improvements in tunnel positioning, graft choice and fixation options [65]. In recent years, increased PTS has been identified as a major contributor to ACL-R failure [66]. In the ACL intact knee, increased anterior tibial translation (ATT) due to an increased PTS puts more pressure on the native ACL or ACL graft. In the ACL deficient knee, increased ATT translates tibiofemoral contact pressures anteriorly [1]. Increased PTS can also lead to graft roof impingement which is an additional cause of

Fig. 6. Demonstrates pre-operative imaging (a and b) of a 49-year-old male with bilateral varus deformity and history of bilateral PCL reconstructions. Post-operative AP radiograph (c) demonstrates a double-level osteotomy.

Fig. 7. Indications for double-level osteotomies in the setting of varus and valgus deformity. LDFA = lateral distal femoral angle; MPTA = medial proximal tibial angle; JLO = joint line obliquity.
ACL-R failure [67,68]. Given the increased awareness regarding increased PTS and ACL-R failure, slope reducing osteotomies have gained popularity in recent years. Slope decreasing osteotomies may be performed in a predominantly uniplanar fashion via Anterior Closing Wedge high tibial osteotomy (ACW-HTO) (Fig. 8) or in a biplanar fashion (MOW or LCW) depending on the presence of concomitant pathology.

**Surgical indications**

Indications for slope-correcting osteotomies are evolving, but the most widely accepted indication is a PTS >12° and >10 mm of ATT in the setting of revision ACL-R. While somewhat controversial, slope-correcting tibial osteotomies can also be considered at the time of primary ACL-R in cases of extreme PTS (>16–20°) or in cases where patients have had multiple ACL-R failures on the contralateral knee [67,69]. There are several contraindications specific to ACW-HTO, including baseline knee hyperextension >10° given the propensity of ACW-HTO to worsen genu recurvatum and varus deformity >5°, given the limited ability to correct coronal deformity via asymmetric anterior wedge resection [70,71]. Thus, if varus deformity >5° is present, then a MOW-HTO or LCW-HTO osteotomy should be considered.

**Surgical techniques**

The goal of ACW-HTO is to correct PTS to 5–8°, although the optimal degree of correction has not been firmly established in the literature. When considering ACW-HTO, there are three techniques to manage the tibial tubercle. The supra-tubercle technique has the theoretical benefit of improved healing given the large surface area of proximal cancellous bone [72]. However, the supra-tubercle technique is challenging given that it avoids altering tension of the extensor mechanism. However, the infra-tubercle technique can be more prone to nonunion, as the patellar tendon distracts the proximal fragment and there is less blood supply to this area of bone compared to the metaphyseal region above the tubercle [73,74]. The tibial tubercle osteotomy (TTO) technique is less technically demanding and allows for translation of the tibial tubercle as needed. However, the addition of the TTO can preclude early range of motion postoperatively leading to potential knee stiffness, especially in the setting of concomitant ACL-R. However, all three techniques can produce appropriate correction and choosing a specific technique often comes down to surgeon preference. [7] (Fig. 9)

**Outcomes**

Literature for slope-correcting ACW-HTO is currently limited to Level 4 case series without long-term follow-up [75]. However, the available data are encouraging and show favourable improvement in clinical (sagittal knee stability and return to sport) and radiographic outcomes. A recent study of 23 patients of patients undergoing revision ACL-R with PTS-reducing osteotomy report a low ACL graft failure rate of 8.7% with all failures being traumatic injuries [71]. Another report of 9 patients who underwent second revision ACL-R combined with a supratubercle ACW reported increased Lysholm and IKDC scores at final follow-up. In this study, the mean PTS decreased from 13.2° to 4.4° postoperatively [72]. Data surrounding slope-correcting osteotomies in primary ACL-Rs are limited given the controversial nature and relative novelty of the procedure.

**Anterior opening wedge osteotomy**

While less common, slope-correcting tibial osteotomies can also be performed in the setting of symptomatic recurvatum (>5°) or increased anterior tibial slope. Genu recurvatum can be the result of osseous or ligamentous abnormalities with osseous abnormalities often occurring as a result of tibial tubercle physeal arrest. With increased anterior tibial slope or a flattened tibial slope, there is a higher remaining posterior tibial translation after PCL reconstruction, which can lead to increased postoperative sagittal knee instability [76]. Therefore, slope-increasing tibial osteotomies are typically performed in the setting of residual posterior knee stability after PCL reconstruction (Fig. 10). Given the rare nature of tibial slope-increasing procedures, there are only a few case reports describing surgical techniques. One recent study described a supratubercle technique using both a plate and large Richards staple for fixation in the setting of failed PCL reconstruction with anterior tibial slope of 13° [76]. Another study described a technique in which a tibial

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**Fig. 8.** Schematic illustration of an anterior closing wedge high tibial osteotomy for increased posterior tibial slope. (A) demonstrates measurement of posterior tibial slope using lateral radiograph of the proximal tibia (B) depicts the tibial tubercle osteotomy and the bony wedge resection. (C) and (D) depict lateral and anterior-posterior views of the completed osteotomy with plate and screw fixation. Reproduced from: Zaidai B, Ozbek EA, Engler ID, et al. Slope-reducing high tibial osteotomy and over-the-top anterior cruciate ligament reconstruction with Achilles tendon allograft in multiple failed anterior cruciate ligament reconstruction. Arthroscopy Techniques. 2022 Nov 1; 11 (11):e2021-8.

**Fig. 9.** Illustration of supra-tubercle (1), tibial tubercle (2) and infra-tubercle (3) anterior closing wedge osteotomies.
tubercle osteotomy was performed followed by the opening wedge HTO [77]. By performing a TTO prior the HTO, the authors avoid any change in patellar height. Future larger cohort studies are needed for evaluate the outcomes of slope-correcting tibial osteotomies and any differences in surgical technique.

Biplanar osteotomies

Biplanar osteotomies can be used to correct both coronal and sagittal malalignment in patients with more complex deformity in a single osteotomy procedure. Combined coronal and sagittal malalignment in the form of increased PTS and varus knee alignment is most commonly seen in patients with ACL deficiency. Therefore, a biplanar MOW-HTO can be performed [78]. While less commonly observed, combined varus and posterior slope-increasing osteotomies can be performed for patients with valgus knee alignment and recurvatum. Similarly, in patients with varus knee osteoarthritis, PCL injuries and decreased PTS, biplanar osteotomies can be performed to correct the varus and increase the PTS. Another indication for a biplanar osteotomy is patients with chronic injuries of the PCL and PLC; a combined varus-correcting and posterior slope-increasing osteotomy can be performed in these cases to improve coronal and sagittal knee stability [79].

Surgical techniques and outcomes

Biplanar osteotomies are most commonly performed in patients with combined increased PTS and varus deformity >5° and therefore this section will focus on cases with sagittal and coronal deformity using both MOW and LCW techniques. The MOW is advantageous in the context of sagittal deformity given the ability to dial in correction to achieve the desired PTS (Fig. 11). When using the MOW to decrease PTS, it is important to ensure that the hinge point is anterolateral on the proximal tibia. Recent work has shown that rotating the hinge point 8.7° internally and angulating the axis 21.6° proximally resulted in a PTS decrease of one degree when opening the osteotomy 10 mm [80]. When performing slope decreasing MOW-HTO, PSI and patient-specific templating can be helpful to accurately achieve this hinge point. The importance of hinge point placement is also demonstrated by the fact that studies have shown that on average MOW-HTOs increase the PTS by 2° [81]. This must be avoided if performing a biplanar osteotomy aimed to decrease tibial slope. One study recently described a technique using a MOW-HTO and an anterior extension osteotomy using a locking plate for the medial osteotomy and 3.5 mm screws from the anterior to posterior direction to secure the extension osteotomy [78]. The LCW technique can also be advantageous for decreasing PTS given its natural tendency to decrease

Fig. 10. (a) Pre- and (b) Post-operative radiographs of an anterior opening wedge high tibial osteotomy and tibial tubercle osteotomy with anteriorization for a twice failed PCL reconstruction. (a) demonstrates a PTS of 4° which was increased to 11° (b). The anterior opening wedge was stabilized with a medial proximal tibial locking plate and the tibial tubercle osteotomy was secured two 4.5 mm cortical screws. PCL = posterior cruciate ligament; PTS = posterior tibial slope.

Fig. 11. Given the triangular shape of the tibia, when performing an opening wedge osteotomy, differential opening of the anterior and posterior aspects of the tibia can change the posterior tibial slope. If opening the osteotomy in the shape of a trapezoid (A), the posterior slope will decrease or be preserved. By contrast, if the osteotomy gap becomes a rectangle (B), the posterior tibial slope of the tibia will increase.
Normal femoral anteversion is de-acetabular impingement, including both anterior and posterior patellar kinematics and lead to an increased Q-angle. Femoral rotational anteversion can be measured using the angle between a line connecting the posterior edge of the distal femoral condyles through the centre of the femoral head and another line connecting the centre of the femoral head through the centre of the femoral neck and the centre of the acetabulum [86]. Rotational deformities of both the femur and tibia can additionally contribute to persistent knee and hip pathology, particularly patellar instability and patellofemoral complaints. Patients with a history of patellar dislocation or subluxation should be evaluated for increased femoral anteversion as increased torsional deformities can influence patellar kinematics and lead to an increased Q-angle. Femoral rotational deformities have also been increasingly studied in the context of femoral acetabular impingement, including both anterior and posterior impingement [85]. Evaluation of the degree of both tibial and femoral rotational deformity can be performed using an axial CT scan. Femoral anteversion can be measured using the angle between a line connecting the centre of the femoral head through the centre of the femoral neck and a line connecting the posterior edge of the distal femoral condyles [86]. Normal femoral anteversion is defined as 12–20° with patients typically asymptomatic unless the discrepancy between the two extremities exceeds more than 10° [87]. Tibial torsion is defined as the relationship between the transcondylar and the transmalleolar axis. For tibial rotational deformities specifically, it is important to evaluate the location of the deformity, particularly whether it is proximal or distal to the tibial tuberosity. A recent study of patients with chronic patellofemoral instability demonstrated that those patients with increased external tibial torsion typically have deformity below the tuberosity and that the degree of torsion is not correlated with a lateralized position of the tibial tuberosity [88]. While no clear indications have been established with respect to rotational deformities, several have suggested that femoral anteverision of >35° or external tibial torsion >43° should be surgically addressed when symptomatic [86,89]. However, a recent study highlighted the highly variable nature of lower limb torsional parameters among asymptomatic patients with Caucasian patients having less hip anteverision and increased tibia external rotation [89]. Femoral osteotomies can be performed proximally at the subtrochanteric level, at the femoral diaphysis, or at the distal femur. The advantage of performing distal femoral osteotomies for rotational deformity is that both coronal and axial plane deformities can be corrected. Similarly for tibial osteotomies, they can be performed in the proximal, diaphyseal, or distal tibia [86].

Outcome studies with respect to rotational deformities largely centre around the use of rotational osteotomies in the context of patellar instability. A recent study of 42 patients with patellar instability and increased femoral anteverision found successful reduction of pain and increase in function (as measured by IKDC and Lysholm scores) with no repeat dislocation in patients treated with derotation DFO [90]. Increased femoral anteverision has also been shown to be a risk factor for failure of isolated MPFL reconstruction in the setting of recurrent patellar instability particularly in patients with significant J-signs pre-operatively [91]. A study of 126 patients with femoral anteverision >30° and patellar instability found that those patients who underwent derotation DFO in addition to MPFL reconstruction had lower rates of residual J-sign and higher Kujala and Lysholm scores post-operatively compared to those patients who underwent isolated MPFL reconstruction [92].

Conclusions and future perspectives

As studies increasingly emphasize the multifaceted nature of lower extremity alignment, osteotomy planning and technique have also become more individualized. This review highlights techniques to correct both coronal and sagittal malalignment through tibial and/or femur-sided osteotomies and the outcomes of these procedures. For patients with malalignment, DLO or biplanar osteotomies may be necessary to correct the degree of malalignment. While the outcomes for DLO and biplanar osteotomies procedures are largely successful, careful planning and precise techniques are required to ensure successful outcomes. Knee surgeons should have a sound understanding of sagittal, coronal, biplanar, double-level and derotation osteotomies. Pre-operative digital 3D planning tools, PSI and navigation as well as in the future robotics and artificial intelligence will likely aid in improving clinical outcomes for patients. (Box 1–6)

Box 1
Key Articles.


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**Box 2**

**Validated Outcomes Measures and Classifications.**

**Outcome measures:**

- International Knee Documentation Committee (IKDC) Knee Scores
- Lysholm Knee Scores
- Knee Injury and Osteoarthritis Outcome Score (KOOS)
- Pain Visual Analogue Scale (VAS)

**Classifications:**

- Refer to Part I, no classification systems discussed in Part II

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**Box 3**

**Key Issues for Knee-based Osteotomies.**

- Evaluation of alignment and the location of alignment should be performed
- Thorough evaluation of status of the cartilage, meniscus and ligaments (collateral and cruciate) of the knee to ensure post-operative knee coronal and sagittal stability and success of the procedure
- Avoid large corrections performed in a single location
- Discuss patient expectations pre-operatively and expected long-term outcomes which may include total knee arthroplasty in the future

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**Box 4**

**Key Issues for Patient Selection.**

**Indication:**

- Pain
- Osteoarthritis (uniblartmental)
- Associated chondral or meniscal disease in setting of joint preservation
- Ligamentous laxity or failure of prior ligament reconstruction

**Preoperative planning evaluation:**

- Weight-bearing radiographs of the knee
- Long-leg alignment films to evaluate coronal alignment
- Lateral tibia radiographs to evaluate sagittal alignment
- CT scanogram needed to evaluate for rotational deformity as needed
- Evaluate ligamentous stability and quality of chondral surfaces and meniscus
- Evaluate pre- and planned postoperative activity level
Author contributions
All listed authors have contributed substantially to this work: literature search and primary manuscript preparation were performed by AL, MGJ, JK, SH and MEK. MO, AG, JDH and VM assisted with editing and finalizing the manuscript. All authors have read and approved the final manuscript to be submitted and published.

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