26 Biomechanics of Osteotomies around the Knee

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26.1 Introduction

Osteotomies around the knee joint have a long tradition and are a well-established and important part of joint-preserving therapy. Numerous studies have shown that at least 30% of the males and almost 20% of the females in western countries have a constitutional varus deformity of more than 3° [1, 2].

The underlying cause of this varus alignment may vary; however, it subsequently leads to increased pressure loads and peak loading areas in the medial compartment resulting in mechanical abrasion. The patient enters a vicious circle of progressive loading leading to increasing cartilage loss and increased varus alignment, which then leads to even more increased loading [3–6]. Malalignment in varus or valgus direction are therefore unfavourable for joint loading and have a major influence on the development or progression of osteoarthritis (OA).

Biomechanical studies have clearly shown that the correction of the malaligned knee unloads the cartilage and that the extent of the shift of the mechanical weight-bearing line correlates directly with the reduction in cartilage loading [7, 8]. Clinical studies have confirmed the positive influence on the pain level and the resilience of the knee joint [9–11]. Therefore, it is well evidenced that an osteotomy is an effective way of realigning and treating malalignment around the knee. Depending on the site of coronal plane malalignment, a varus or valgus correction osteotomy can be performed in an opening- or closing-wedge manner. These should be always done at the site of malalignment and hence these can be carried out laterally or medially at the distal femur or proximal tibia.

One of the reasons for the recently increasing interest in osteotomies is the improved technique, which allows the procedure to be performed safely without loss of correction. These advances have been made possible by the introduction of internal plate fixators, combined with an improved osteotomy technique (biplanar technique). Angle-stable internal fixators have previously proven its effectiveness in trauma settings [12–14].

26.2 General Aspects of Osteotomies around the Knee

26.2.1 Degree of Osteoarthritis

The malalignment-correcting osteotomy causes a shift of the peak load areas from the painful joint compartment to the intact opposite side. The clin-

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ical outcome tends to be more favourable in knees with only moderate OA compared to advanced unicompartmental OA [10]. In the case of a more severe OA, the patient must be informed that a decrease of symptoms and increase of activity, but no complete relief of symptoms and pain can be expected. If there is a considerable extension deficit (over 10°), it must be considered whether an additional removal of intra-articular osteophytes could be helpful [15].

The conventional valgus-producing tibial head osteotomy is not indicated in cases of substantial loss of the outer meniscus and manifest lateral OA (extensive third- or fourth-degree damage, cartilage ulcers). In case of doubt, a stress radiograph should be taken under valgus load. If this results in a loss of height in the lateral joint section, a total knee arthroplasty is more appropriate [15].

26.2.2 Patellofemoral Instability

Valgus deformities can occur in combination with lateral instability of the patella. This problem can be well treated with an osseous and soft tissue combined medial intervention. The biplanar distal femoral varus osteotomy allows a correction of the axis and, if necessary, torsion, while at the same time reconstruction of the medial patellofemoral ligament can be performed using the same approach [16].

26.2.3 Patellofemoral Osteoarthritis

Many patients with unicompartmental OA also show degenerative changes in the patellofemoral joint. The evaluation of these patients is challenging. The medical history and the clinical examination are important factors. The retropatellar changes should not be decisive for the decision against a joint-preserving procedure such as osteotomy. Leg axis correction normalizes the alignment of the extensor mechanism and generally improves the loading conditions in the trochlear groove. If an HTO is indicated, an opening-wedge osteotomy using a biplanar technique with distal tuberosity incision can be selected to avoid distalization of the patella and an increase in patellar pressure [17]. Therefore, patellofemoral degenerations that are clinically mostly asymptomatic do not represent a contraindication for osteotomy around the knee in the case of unicompartmental OA [18].

26.2.4 Imaging

In all patients with possible OA in the knee anteroposterior, lateral radiographs with patella view as well as long-leg full weight-bearing views should be performed. When making the long-leg radiographs, it is important to ensure that both knees are extended maximally and the patellae are pointing forward. MRI scans may add valuable information on cartilage condition, meniscus, ligament and soft tissue damage. Also the location of nerves and vessels relative to the area of deformity correction can be assessed [19]. If a torsion deformity is found at physical examination, a computerized tomography (CT) scan with measurements of axial slides at standardized positions is mandatory. Furthermore, combined single photon emission-computerized tomography and conventional computerized tomography (SPECT/CT) has proved to be helpful in the assessment, pre- and postoperatively, of osteotomy patients [20, 21]. Mucha et al. have shown a significant decrease of bone tracer uptake (BTU) after HTO in the medial joint compartments in patients with medial compartment overloading due to varus malalignment (Fig. 26.1) [21]. The authors concluded that the evaluation of patients before and after HTO using SPECT/CT with regard to the mechanical leg alignment provides the surgeon with helpful additional information about the loading history of the knee joint. SPECT/CT could be further used to identify the optimal individualized correction for each patient and clinical scenario [21]. It is the only imaging modality, which allows a direct visualization of the unloading effect in the relevant compartment after osteotomy.

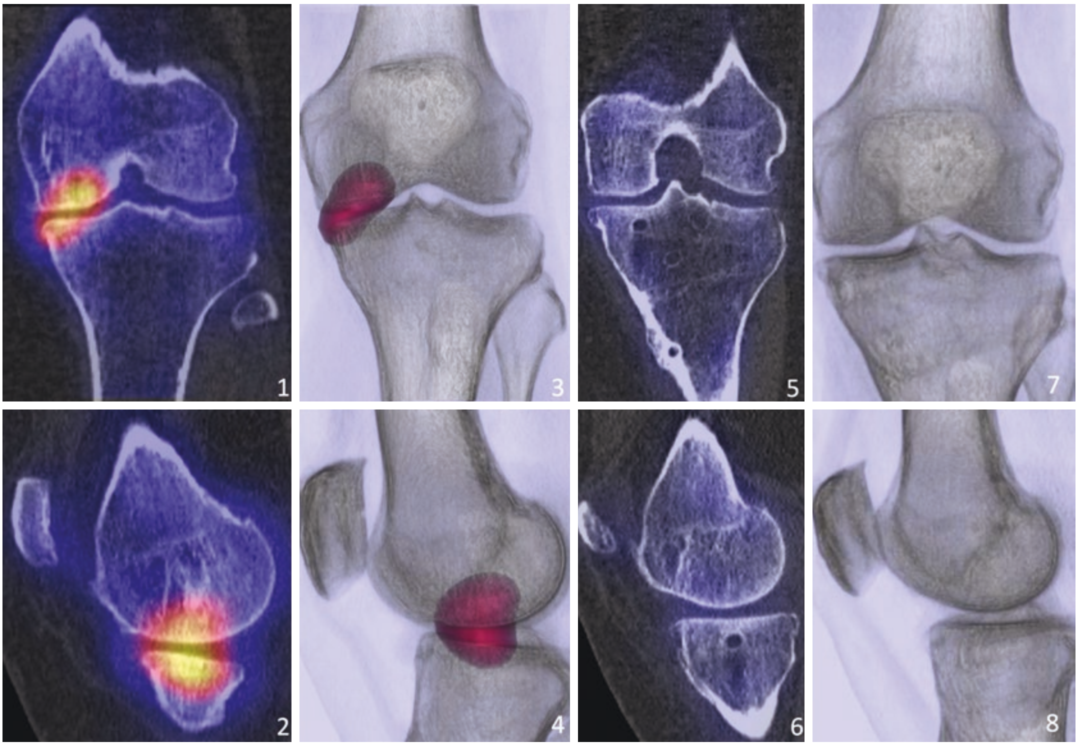

Fig. 26.1 *Left* SPECT/CT images (1, 2) and 3D radiolucent reconstructions (3, 4) of a 52-year-old female patient before HTO showing medial overloading. *Right* SPECT/CT images (5, 6) and 3D reconstructions (7, 8) 16 months postoperatively reveal an unloading effect of the medial joint compartment and a consolidation of the osteotomy gap. Reprinted with permission from Knee Surg Sports Traumatol Arthrosc (2015) 23:2315–2323

26.3 Biomechanical Considerations of High Tibial Osteotomy

Both valgus and varus malalignment are unfavourable for the joint mechanics and have a major influence on the development or progression of OA. A correction of the axis deformity thus results in cartilage decompression; the position of the loading axis in the frontal plane correlates directly with the tibiofemoral cartilage pressure distribution in the knee [7]. The normalization of the mechanical load conditions leads to a positive influence on the homeostasis of the knee joint.

Under normal conditions, the mechanical axes of femur and tibia are colinear (articular surface of the tibia averages 3° varus (medial proximal tibia angle, MPTA) and that of the femur 3° valgus (mechanical lateral distal femoral angle, mLDFA) relative to the mechanical axis) and the mechanical weight-bearing line (WBL) crosses the knee joint in the area of the medial spina (Fig. 26.2) [22]. In a neural aligned knee, 55–70% of the load is transmitted on the medial compartment during the stance phase of gait [23]. A deviation in the varus or valgus direction can be caused by a bony malposition in the femur and/or tibia, by a defect in the knee joint or by ligamentous instability. In a varus aligned knee, a deviation of 1° varus from the neutral alignment will cause an increase of the medial load of 5% [24].

First described by Jackson and Waugh in [25], high tibial osteotomy (HTO) is a well-established procedure for treating medial compartment OA of the varus deformed knee. In HTO, the bone of the proximal tibia is cut, and either the osteotomy gap is opened in a wedge shape (opening-wedge HTO) or a bone wedge is removed (closing-wedge HTO). With correct planning, it can normalize the bony anatomy and therefore create

Fig. 26.2 50-year-old male patient before (**a**) and after (**b**) opening-wedge high tibial osteotomy (HTO) due to symptomatic varus alignment. The mechanical weight-bearing line (brown) crosses the knee joint preoperatively (**a**) in the medial compartment and after HTO (**b**) in the area of the lateral spina. The postoperative correction (**b**) of the medial proximal tibial angle (MPTA) is 3°, which results in a horizontal joint line (joint line convergence angle (JLCA), the angle between the tangent to the distal femoral condyles and the tangent to the tibia plateau). The mechanical lateral distal femoral angle (mLDFA) remains unaffected with 88° valgus (**a**, **b**)

physiological loading conditions for the entire leg (Fig. 26.2). The gait pattern is normalized and the dynamic distribution of load becomes physiological.

Regardless of the type of the osteotomy, the biomechanical objective of HTO is to realign the WBL in the coronal plane. The aim is to achieve the shift of the WBL from the arthritic compartment to the opposite tibiofemoral healthy compartment [7, 26]. Fujisawa et al. [27, 28] recommended to align the WBL of HTO through the 65–70% coordinate of the width of the tibial plateau, which has been refined recently to 62.5% towards to the Mikulicz line to restore the kinematic alignment profile [1, 29, 30]. Hence, the influence of the targeted limb alignment after HTO on cartilage repair is under heavy debate in literature [31–35]. In a recent retrospective comparative study, it has been reported that no difference between overcorrected knees with mean femorotibial angle of 165° and moderately corrected knees with mean femorotibial angle of 170° was found [31]. Martay et al. proposed correcting the weight-bearing axis to 55% tibial width (1.7°–1.9° valgus) for the optimal distribution of medial and lateral contact stresses [32]. Nakayama et al. found a large amount of correction in opening-wedge HTO with a resultant joint line obliquity of 5° or more may induce excessive shear stress to the articular cartilage [33]. Similarly, Zheng et al. reported that balanced loading occurred at angles of 4.3° and 2.9° valgus for the femoral and tibial cartilage, respectively [34]. Contradictory, Trad et al. suggested that a balanced stress distribution between two compartments was achieved under a valgus hypercorrection angle of 4.5° [35]. Clinical studies suggest that excessive overcorrection leads to poor functional outcomes and degeneration in the lateral compartment, while undercorrection does not relieve the pain of the medial compartment [27, 36, 37].

To date, it is unclear how articular cartilage repair in the medial compartment is affected by the grade of preoperative degeneration of the articular cartilage. Koshino et al. reported that knees with advanced degeneration of articular cartilage at lateral closing-wedge HTO showed better repair compared with knees with early degeneration [38], whereas Fujisawa et al. reported conflicting arthroscopic findings [28].

As a result, the question remains unsolved whether a “safety corrective range” for HTO in patients with OA exists. The effect of excessive stress on soft tissue wear or repair and the remodelling process after corrective osteotomy is still unknown.

26.3.1 Mediolateral Stability

Of particular importance in HTO patients is the medial collateral ligament (MCL). A medial opening-wedge HTO increases the strain on the superficial distal part of the MCL by spreading the osteotomy gap, whereas a lateral closing-wedge procedure has only a minor effect on the MCL. In this context, Agneskirchner et al. have shown the opening-wedge HTO without MCL release resulted in a significant increase of the pressure medially. Only after a complete release of the MCL a significant decrease of pressure medially was observed after opening-wedge HTO [7]. Conversely, if HTO has to be performed in case of a tibial valgus deformity [2], lateral opening-wedge HTO technique or alternatively, a medial closing-wedge HTO can be performed to correct the valgus leg alignment [39]. However, in the medial closing-wedge HTO, the medial MCL laxity has been found to increase [40, 41]. Hence, it was suggested to perform a surgical reefing procedure at all times to tighten the MCL in these patients [40].

26.3.2 Influence of Tibial Slope Change on Stability

In recent years, it has been shown that the inclination of the tibial plateau in the sagittal plane ("slope") affects the stability of the knee joint [42–44]. Physiologically, the tibial plateau is slightly tilted posteriorly. To describe the posterior inclination of the tibial plateau, the angle of the medial tibial plateau to the right angle to the proximal tibial axis is usually stated in literature. The mean values of the tibial slope reported in literature vary between 5° and 8° with a variance between 0° and 14°. In 19% of the population, there is a posterior slope of more than 10° [45]. An increased tibial slope can accentuate an anterior instability; however, it may also lead to a reduction of the posterior drawer, whereas a decreased tibial slope leads to a reduction of an anterior knee instability [43, 46].

It is well known that all techniques which correct frontal plane misalignment may also change sagittal plane alignment [47, 48]. Posterior tibial slope is considered to be an important factor in knee joint kinematics [42, 49–53]. Schaefer et al. have analysed the frontal and sagittal femorotibial knee alignment after opening- and closing-wedge HTO. Postoperatively, tibial slope had decreased by −0.5° in closing-wedge HTO and increased significantly by +3° in opening-wedge HTO [54].

The combination of symptomatic varus OA with significant knee instability due to overloading of the antero- and posterolateral structures is quite common in the younger group of patients and can be well treated by an HTO [42, 55]. Even a relative loosening of the collateral ligament can be easily eliminated by an opening-wedge HTO [15].

The following paragraphs provide biomechanical principles on how changes in the sagittal and frontal plane of the knee may alter the stability of the joint [56].

26.3.2.1 Coronal Alignment

The lateral joint opening and the tension of the anterior cruciate ligament (ACL) on human knee specimens with neutral mechanical axis and with varus axis have been measured by van de Pol et al. in 2009 [57]. There was no lateral opening of the joint in the neutral axis, but it was increased in the varus axis. The tension in the ACL also increased significantly with increasing varus deformity.

In a biomechanical study, La Prade et al. examined the effect of the varus axis on the posterolateral structures [58]. In this study, a significant increase in varus rotation (ligamentous varus) occurred after transecting the posterolateral structures. However, the opening-wedge osteotomy of the tibia was able to reduce both the varus rotation and external rotation, which were caused by the transection of the posterolateral structures. La Prade et al. also attribute the stabilizing effect of the osteotomy to increased tension in the medial collateral ligament.

A recent meta-analysis has shown that frontal deformities have no influence on the risk of primary ACL ruptures [59]. However, various studies have shown that patients with recurrent instability after ACL reconstruction were significantly more likely to have a varus deformity (>5°) [59–61].

Clinical studies are also available on the influence of frontal alignment on the results of posterior cruciate ligament (PCL) and posterolateral reconstruction [62, 63]. In both studies, varus deformity was considered as a risk factor for a reinjury after PCL and posterolateral reconstruction.

26.3.2.2 Sagittal Alignment

In a biomechanical study, Agneskirchner et al. have changed the tibial slope in human cadaveric knees by flexion osteotomies and then measured the anterior tibial translation of the tibial plateau to the femur [42]. This study demonstrated that an increase of posterior slope intensifies the anterior translation of the tibia. In addition, the tibiofemoral contact area and pressure was shifted anteriorly, resulting in decompression of the posteromedial tibial plateau.

Similarly, Giffin et al. were able to show that under axial compressive load increased slope of the tibia led to an anterior translation of the tibia in relation to the femur [44]. In addition, the in-situ forces in the ACL increased with increasing slope. Shelburne et al. were able to confirm the results of both studies in a computer model [64]. In the computer simulation, an increase in slope led to an increased anterior translation during daily activities like standing, squatting or walking.

Yet, there are three meta-analyses that can show that both the medial tibial slope and the lateral tibial slope are a risk factor for suffering an ACL rupture [59, 65, 66]. In this context, the study of Webb et al. should be highlighted: It was found that the risk of a further ACL injury was increased by factor 5 in patients with a slope of >12° [67]. Significantly fewer studies deal with the influence of the posterior tibial slope on posterior instability. Schatka et al. were able to show that in the uninjured knee, a low posterior slope correlates with an increased posterior translation of the tibia [68]. Bernhardson et al. found that a lower posterior slope is a risk factor for a PCL rupture [69].

26.3.2.3 Valgus HTO in Patients with Anterior Instability

The triad of anterior instability, medial OA and varus deformity [70, 71] as well as an isolated double or triple varus deformity without medial OA [61, 72, 73] are recognised as indications for HTO in patients with anterior instability [56]. Double varus occurs due to tibiofemoral varus alignment and separation of the lateral tibiofemoral compartment due to deficiency of lateral soft tissues (= joint line conversion angle, JLCA) [74]. Triple varus occurs due to deficiency of the posterolateral corner ligament and results in varus with recurvatum. This arises because of varus osseous alignment (primary varus), separation of lateral tibiofemoral compartment (double varus) and increased external rotation and hyperextension caused by posterolateral instability [75].

With regard to postoperative results, all studies on HTO in anterior instabilities show that clinical scores can be improved by HTO alone or by the combined procedure (HTO plus ligament reconstruction) [70–72, 76]. It is irrelevant whether the ligament reconstruction is performed in one or two stages [76]. However, the increased complication rate of 63% must also be pointed out for the combined procedure [70].

26.3.2.4 Slope Correction during Valgus HTO in Patients with Anterior Instability

As described above, tibial slope can also be changed during valgus HTO. Unfortunately, this can happen unintentionally when the surgeon is inexperienced and the slope is not observed or controlled during a tibial head osteotomy (K-wire and lateral image intensifier control). It is therefore inevitable that this potential change is taken into consideration every time an osteotomy is performed on the tibial head. The intentional reduction of the slope can clearly improve anterior instability—in contrast, an increase of the tibial slope can reduce posterior instability. Arun et al. showed that patients after HTO with a posterior slope reduction of more than 5° achieved better functional scores than patients with a slope reduction of less than 5° [77].

Hence, in addition to HTO the intentional and correct reduction of the tibial slope can improve postoperative results in patients with anterior instability. However, in many cases an ACL reconstruction may also be necessary [78].

26.3.2.5 Slope Correction during Valgus HTO in Patients with Posterior Instability

Studies have shown that functional clinical scores and subjective stability can be improved by an isolated valgus medial opening-wedge HTO [72, 79, 80]. Often effectively enough that secondary ligament reconstruction was no longer necessary. Reichwein and Nebelung were able to significantly improve knee function in patients after failed PCL reconstruction with an isolated slope-increasing osteotomy [81].

26.4 Biomechanical Consideration of Distal Femoral Osteotomy

Distal femoral deformities are observed in valgus deformities and also in severe varus deformities. However, there are some biomechanical differences compared to the proximal tibia. The lever arm is longer and the surface at the level of the osteotomy is smaller on the femoral side. There is no "hinge-preserver" such as fibres of the proximal tibiofibular joint in the area of the safe zone. Furthermore, the blood circulation at the distal femur differ fundamentally from the proximal tibia [82, 83]. As a result, DFO is inherently more unstable and considered to be difficult procedures with high potential risk of complications (3.2% non-union and 3.8% delayed union) [84–86]. Distal femoral osteotomies can be performed with lateral opening- or medial closing-wedge osteotomy. However, healing complications and irritation of the iliotibial band by the fixator have been described more frequently for the lateral opening distal femoral osteotomy [87]. For this reason, the medial closing osteotomy of the distal femur has become increasingly popular in recent years [88, 89].

Varus-producing osteotomies of the distal femur are a good surgical option for the purpose of unloading the affected lateral compartment and correcting underlying valgus malalignment in high-demand active patients with symptomatic unicompartmental OA [90, 91]. While clinical studies have demonstrated successful outcomes following distal femoral varus osteotomies (DFVO) in the treatment of lateral compartment OA [86, 89, 92–95], to date there is scarce knowledge on biomechanical effects of the load redistribution produced by the DFVO in orthopaedic literature. In a recent biomechanical cadaveric study, Quirno et al. found progressive unloading of the lateral tibiofemoral compartment with increasing DFVO correction angles (25% decrease in mean contact pressure with 15° osteotomy) [96]. The authors recommended, when performing a DFVO for valgus malalignment, to aim for an overcorrection of 5° to restore near-normal contact pressures and contact areas in the lateral compartment rather than the traditional teaching of correcting to neutral alignment [96]. Conversely, clinical studies are less conclusive with regard to their recommended correction of valgus malalignment with no uniform trend towards any particular correction goal being definitive [92–94, 97].

Based on biomechanical examinations and clinical experience, biplanar osteotomies for the distal femur are recommended [98, 99]. The biplanar technique has geometrical advantages by reducing the volume of the osteotomy, approximating the metaphysis with better bone healing, increasing axial stability, protecting against the potential issue of malrotation, and allowing open reduction in case of a hinge fracture [12, 98, 99].

The biplanar technique, along with angle-stable plate fixators, can be used both laterally for valgus corrections and medially for varus corrections with very good midterm results and patient satisfaction [84, 100, 101].

26.5 Biomechanical Considerations of Intra-Articular Osteotomy

The deviation of the WBL can be caused by a bony deformity of the femur and/or tibia (primary, constitutional deformity) on the one hand, and by a defect in the knee joint itself on the other hand.

For metaphyseal deformities, opening and closing tibial osteotomies can be performed, as developed for the correction of constitutional deformities. If the deformity is located clearly within the joint, an intra-articular osteotomy can be discussed [102–105]. They directly address the incongruent joint surface and can be used for deformities in the sagittal and coronal plane. Indications for an intra-articular osteotomy may be: malunions of the tibial plateau with significant intra-articular depression and/or steps; deviation of Mikulicz line in the overloaded compartment; flexion−/extension deformity with significant restriction of range of motion but also constitutional deformities such as Blount disease, Ellis–van Creveld syndrome and some types of achondroplasia [19, 106].

Posttraumatic intra-articular deformities state the main indications for corrective intra-articular osteotomies. This is explained by the fact that tibial plateau fractures may result in knee incongruity and instability. The incongruity is produced by the mismatch between the tibial and femoral articular surfaces [107]. The lack of containment of the rim of the joint generates instability. The biomechanical aim of the treatment is to restore the rim and its containment and thus stability, as well as a physiological WBL.

26.5.1 Tibial Plateau Widening

Insufficient anatomical reduction of the articular surface may produce secondary depression with angular deformity, widening of the tibial plateau and subluxation of the joint. The goal of correction is to re-establish “normal” relationships in relation to the contralateral side. The widening of more than 5 mm is usually considered to have worse functional outcomes [102, 108]. Johannsen et al. have distinguished residual widening within normal variation from pathological widening and found even a lower threshold with 2.1 mm [109]. Kumar et al. suggested that 4% of extra width relative to femoral articular surface can be considered normal for the tibia plateau [108]. However, pathological widening puts undue stress on surrounding ligaments and capsule but also alters biomechanics which could affect the knee function [108]. An intra-articular closing-wedge osteotomy can be performed to restore the width and height of the tibial plateau and thus joint congruity and stability.

26.5.2 Unicompartmental Angulation

As described by Paley et al., the physiological mechanical proximal tibia angle measures 87 ± 3 degrees [110]. Deviations between the articular surface and the 87° proximal tibia angle are often caused in posttraumatic situations by a malunited split wedge plateau fragment after a tibia plateau fracture. Clinically relevant deviation which requires surgery may include a change of ≥5° in lower limb alignment (varus or valgus), articular surface compression ≥5 mm, and a plateau shift and axial instability ≥5° [102]. A change in posterior slope angle of ≥10° is also considered to be an indication for operation [102].

The correction of unicompartmental angulation is normally performed by an opening-wedge intra-articular osteotomy in the plane of the deformity and with a hinge at its apex (at the level of the tibial spines) [107]. Thereby, the joint line can be elevated in order to restore joint congruity and containment of the tibial plateau rim with respect to the femoral condyle, and thus malalignment will be corrected. Beside relevant articular deviations, surgical indications include joint instability and residual knee pain in daily activities [111].

26.6 Conclusion

The osteotomy around the knee is an evidence-based joint-preserving procedure for the therapy of unicompartmental osteoarthritis with good long-term results. A correction of the axis deformity results in cartilage decompression—the position of the loading axis in the frontal plane correlates directly with the tibiofemoral cartilage pressure distribution in the knee. The normalization of the mechanical load conditions leads to a positive influence on the homeostasis of the knee joint. However, the recommended target for alignment correction is under debate for both the HTO and the DFO with regard to the biomechanical and clinical findings.

Posterior tibial slope is considered to be an important factor in knee joint kinematics. All techniques which correct frontal plane misalignment may also change sagittal plane alignment. It is well known that opening-wedge HTO generally increases and closing-wedge HTO decreases tibial slope. An increased tibial slope can accentuate an anterior instability, however may also lead to a reduction of the posterior drawer, whereas a decreased tibial slope lead to a reduction of an anterior knee instability.

The osteotomy around the knee is a reliable technique with significant biomechanical effects on the entire lower extremity and, if performed correctly, can bring significant benefits to the patient.

Declaration of Competing Interest **No conflicts of interest.**

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