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Osteotomies: Advanced and Complex Techniques

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11.1 3D Planned and Printed Patient Matched Osteotomy

11.1.1 Introduction

We started performing precise surgery based upon CT plans in the last century – the first embodiment of this approach was a robotic assistant built for total knee replacement, the “Acrobot” [1]. Abundant evidence now exists to confirm that assistive technologies enable surgeons to achieve their preoperative goals [2]. The concept of planned surgery is therefore not novel. Patient-matched instruments share several key elements with the robotic platform, and these formed the basis of this current project. The essential elements include image segmentation, planning, and registration. We applied the know-how of these dimensions to design and build patient-matched guides for a range of tasks using biocompatible polymer 3D printers. Having established a workflow for arthroplasty, the adaptation of the same principles to osteotomy was a short step, requiring software to be developed to deliver semiautomated useful information regarding limb segment alignment and the shapes of bones.

11.1.2 Method

To plan any procedure in 3D, images are acquired. Currently, we use CT for the bone model and EOS® to confirm both limb alignment and the impact of any shortening on the spine and entire body (Fig. 11.1). Using CT, the bone can be segmented out semiautomatically, using Hounsfield unit thresholds from a low-dose protocol [3]. This is rather easier in deformity correction than in arthrosis, as the joint spaces are better preserved. When segmenting for arthroplasty, in the presence of substantial arthrosis, separating out bone surfaces can be both tedious and time-consuming, as it needs significant human input to complete the task.

Having obtained the bone models, the task of planning can be semiautomated. We have already shown that there is in effect a lookup table of

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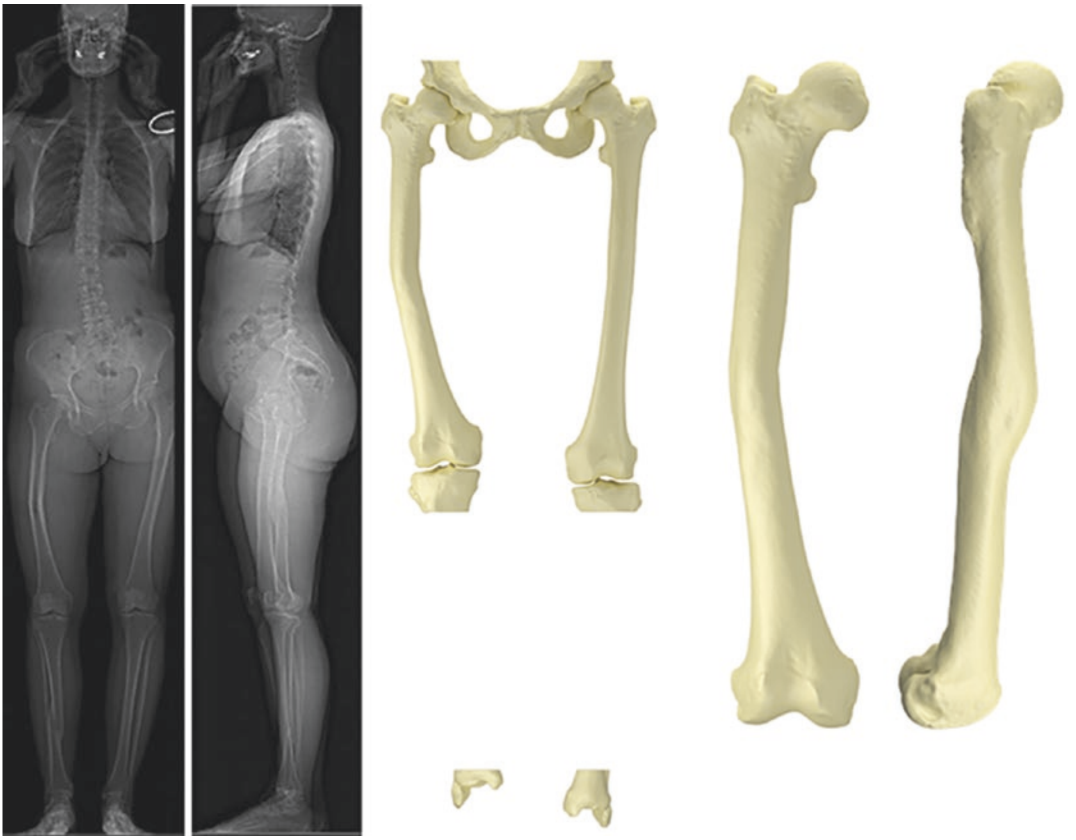
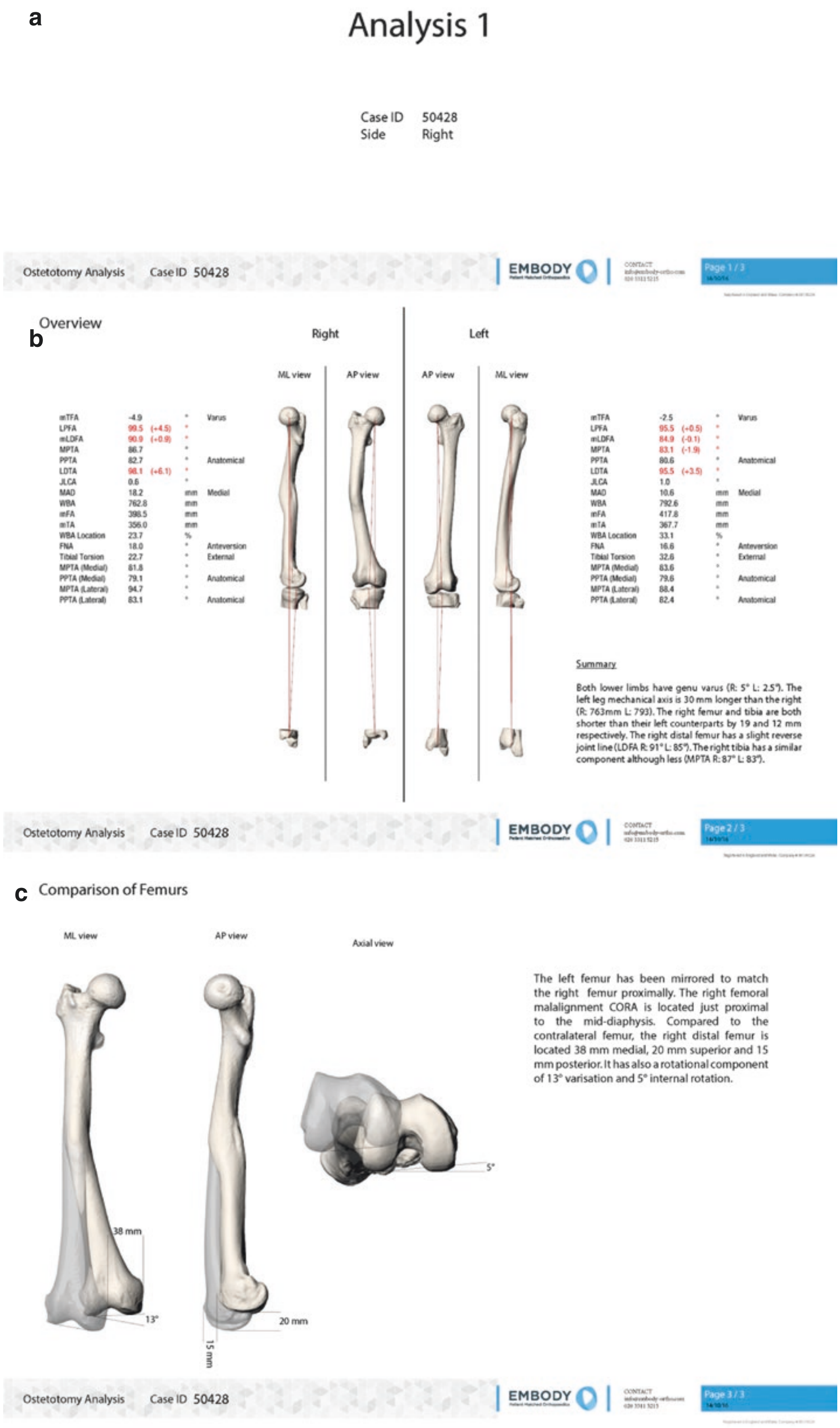


Fig. 11.1 Anteroposterior and lateral radiographs for assessment of limb alignment (left) and 3D model of EOS® imaging for preoperative planning (right)

deformity in varus: the supine deformity is increased by some 2° on weight bearing and by some 2° more in the stance phase of gait [4]. For corrective osteotomy of the proximal tibia, for instance, we are still exploring the impact of correction on gait, and our current understanding is less than ideal, especially when there is some chondral loss. So, as a group we do not support the "Fujisawa" point; instead we support offering the surgeon the option to correct alignment as much as he or she chooses, with correction to neutral alignment an option or any variant of this. Having undertaken less than 50 corrective osteotomies using full 3D planning, as a group we still are less than confident in how much correction is optimal for any one case.

In posttraumatic deformity correction, the task is somewhat simple. In general, the aim is simply to restore to the pre-fracture state. Using a Matlab script written by one of the coauthors (SJC), the good leg is simply flipped onto the bad leg, matching the larger bone segment. This allows the surgeon to appreciate the extent of the problem.

The deformity is then analyzed. In general, there is always a degree of rotation and translation, with the rotation always being "out of plane" of either an anteroposterior (AP) or a lateral projection, and the translation usually includes some substantial shortening. The exact extent of these angles and translations are provided semiautomatically with the other limb for comparison (Fig. 11.2). After describing the extent of the shortening and rotation, the planner then "simply" corrects the distal segment and chooses a plane for the correction that allows the bone segments to slide and rotate, restoring medullary continuity so that intramedullary fixation is an option at least (Fig. 11.3).



Analysis 1

Case ID 50428
Side Right

Ostetotomy Analysis Case ID 50428

Overview

mTFA	-4.9		°	Varus
LPFA	99.5	(+4.5)	°	
mLDFA	90.9	(+0.9)	°	
MPTA	86.7		°	
PPTA	82.7		°	Anatomical
LDTA	98.1	(+6.1)	°	
JLCA	0.6		°	
MAD	18.2		mm	Medial
WBA	762.8		mm	
mFA	398.5		mm	
mTA	356.0		mm	
WBA Location	23.7		%	
FNA	18.0		°	Anteversion
Tibial Torsion	22.7		°	External
MPTA (Medial)	81.8		°	
PPTA (Medial)	79.1		°	Anatomical
MPTA (Lateral)	94.7		°	
PPTA (Lateral)	83.1		°	Anatomical

mTFA	-2.5		°	Varus
LPFA	95.5	(+0.5)	°	
mLDFA	84.9	(-0.1)	°	
MPTA	83.1	(-1.9)	°	
PPTA	80.6		°	Anatomical
LDTA	95.5	(+3.5)	°	
JLCA	1.0		°	
MAD	10.6		mm	Medial
WBA	792.6		mm	
mFA	417.8		mm	
mTA	367.7		mm	
WBA Location	33.1		%	
FNA	16.6		°	Anteversion
Tibial Torsion	32.6		°	External
MPTA (Medial)	83.6		°	
PPTA (Medial)	79.6		°	Anatomical
MPTA (Lateral)	88.4		°	
PPTA (Lateral)	82.4		°	Anatomical

Summary

Both lower limbs have genu varus (R: 5° L: 2.5°). The left leg mechanical axis is 30 mm longer than the right (R: 763mm L: 793). The right femur and tibia are both shorter than their left counterparts by 19 and 12 mm respectively. The right distal femur has a slight reverse joint line (LDFA R: 91° L: 85°). The right tibia has a similar component although less (MPTA R: 87° L: 83°).

Ostetotomy Analysis Case ID 50428

Comparison of Femurs

The left femur has been mirrored to match the right femur proximally. The right femoral malalignment CORA is located just proximal to the mid-diaphysis. Compared to the contralateral femur, the right distal femur is located 38 mm medial, 20 mm superior and 15 mm posterior. It has also a rotational component of 13° varisation and 5° internal rotation.

Ostetotomy Analysis Case ID 50428

Fig. 11.2 (**a**–**c**) Preoperative analysis and planning steps

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CASE 50428

OSTEOTOMY PSI

Operative Technique and Parts List

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Parts List

Part A Main Osteotomy Guide

Part C & D: Inserts (x2)

Part E: Correction Block

Part B: Epicondylar Guide Rod

ADDITIONAL PARTS REQUIRED:
6 x 3.2 mm diameter Bone Pins

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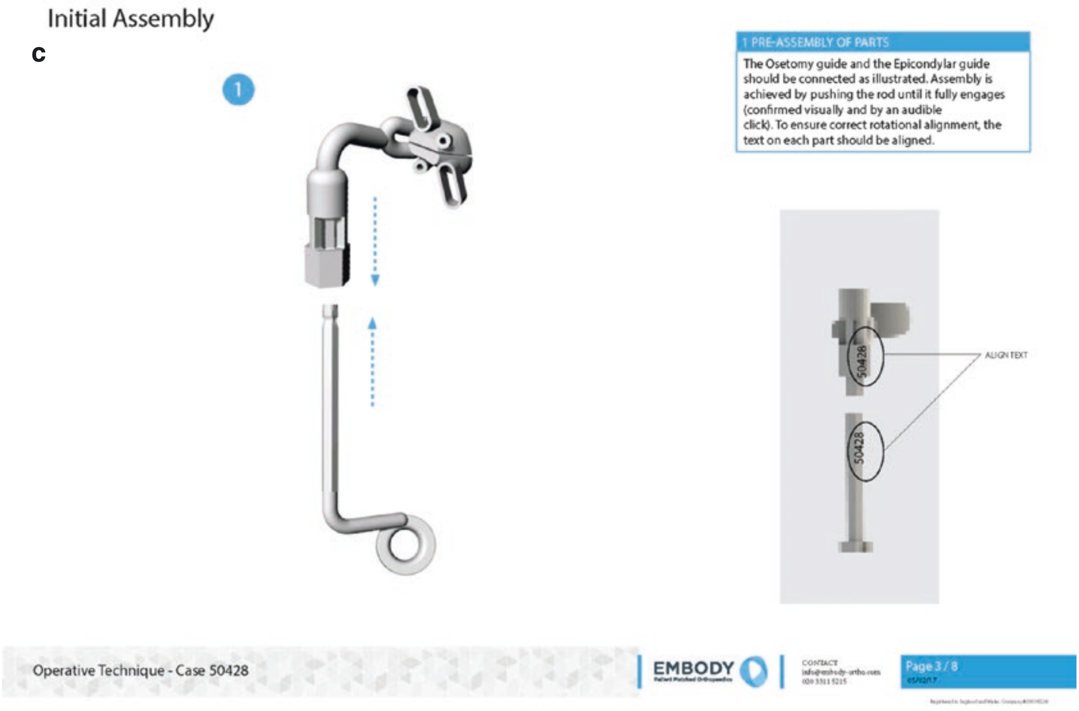
Fig. 11.3 (**a**–**h**) Operative technique and parts list



Initial Assembly

c

1 PRE-ASSEMBLY OF PARTS

The Osetomy guide and the Epicondylar guide should be connected as illustrated. Assembly is achieved by pushing the rod until it fully engages (confirmed visually and by an audible click). To ensure correct rotational alignment, the text on each part should be aligned.

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d

2 GUIDE LOCATION SKIN

Place the later epicondyle as a reference point for the epicondylar guide. This will guide the incision point.

3 GUIDE LOCATION BONE

Once the incision is made, place the guide osteotomy guide on the bone. The guide should match the bone surface.

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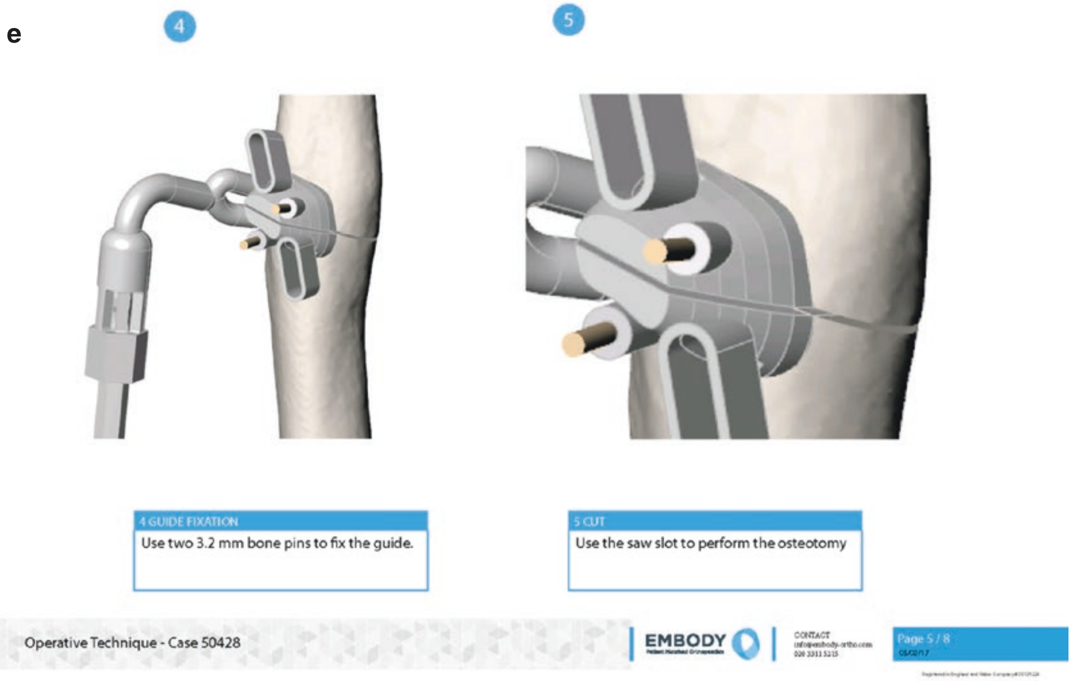
Fig. 11.3 (continued)



4 GUIDE FIXATION

Use two 3.2 mm bone pins to fix the guide.

5 CUT

Use the saw slot to perform the osteotomy

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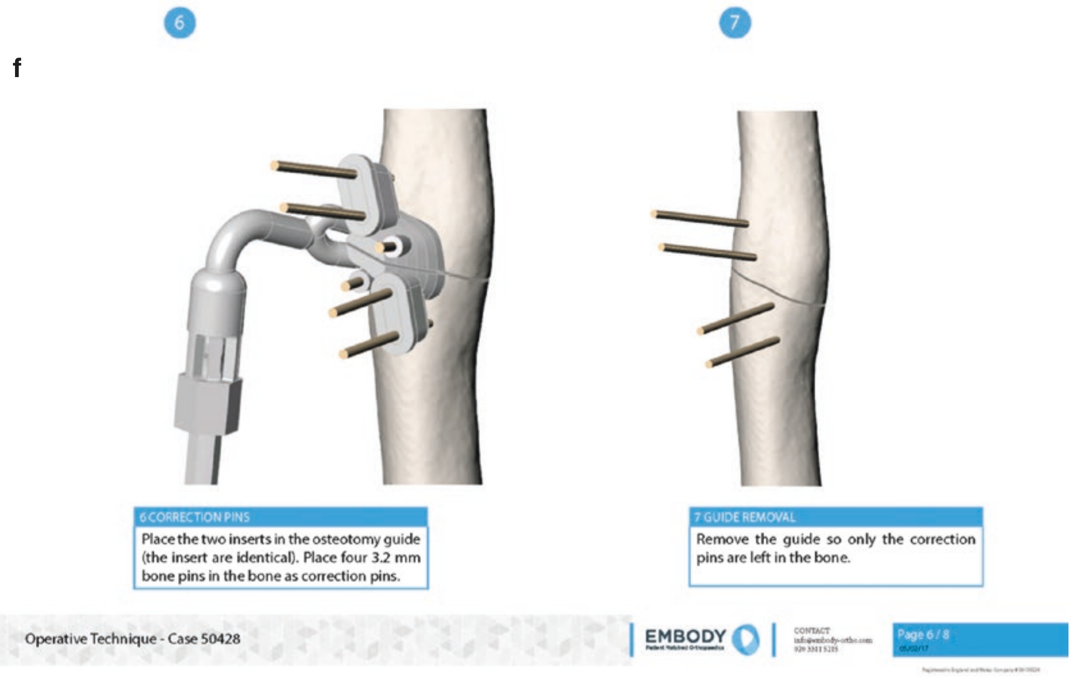

6 CORRECTION PINS

Place the two inserts in the osteotomy guide (the insert are identical). Place four 3.2 mm bone pins in the bone as correction pins.

7 GUIDE REMOVAL

Remove the guide so only the correction pins are left in the bone.

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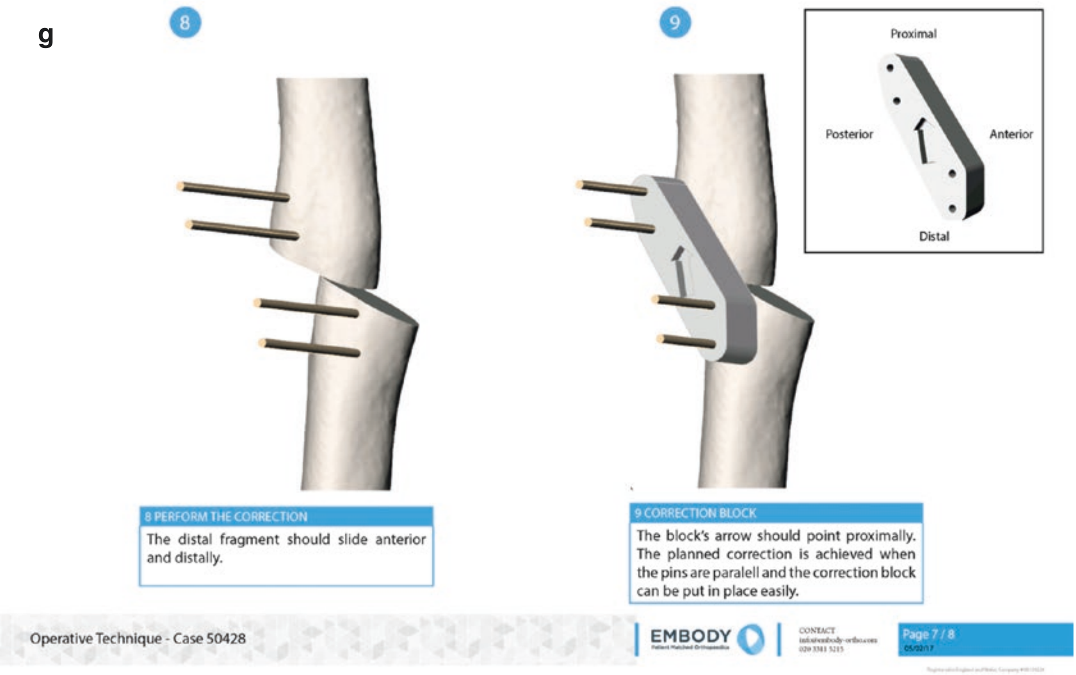
Fig. 11.3 (continued)

g



8 PERFORM THE CORRECTION

The distal fragment should slide anterior and distally.

9 CORRECTION BLOCK

The block's arrow should point proximally. The planned correction is achieved when the pins are paralell and the correction block can be put in place easily.

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h

Fixation

10. FIXATION

The nail visualised is a Smith and Nephew Trigen FAN nail 36 cm. The nail can be position with the correction pins in place.

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Fig. 11.3 (continued)

Fig. 11.4 Fluoroscopy for confirmation of positioning

Guide design is generic in some features, so it can be semiautomated. Two elements need consideration: multipoint registration and soft tissue access. Ideally, subcutaneous features distant to the osteotomy are employed to improve gross positioning. Local features are also used, over as large an area as is practicable. Finally, fluoroscopic control is used to confirm positioning (Fig. 11.4).

Implant selection can be made during planning: the exact length of the fixation device and the exact screw lengths can be predicted with confidence, reducing the opportunity for error in screw length selection. Detailed planning of sizes at this stage reduces the cost and duration of the procedure by ensuring that exactly the right size components are ready beforehand.

Intraoperatively, both the detailed plan and the instruments provided for 3D planned corrective osteotomy reduce the level of anxiety considerably. At operation, the soft tissue access is of major importance. Inevitably, considerable manipulation of the bone fragments and the overlying muscle takes place, so an extensile approach should be considered and care taken to release any tethering of muscle or fascia before osteotomy and correction. We use infiltration of local anesthetic and do not employ a tourniquet.

11.1.3 Results

Since 2012, we have undertaken 49 corrective osteotomies. Eight of these have been combined osteotomies and arthroplasties. Two have combined a corrective osteotomy and total knee arthroplasty, while six have included a partial knee replacement. Two infections have occurred, both in soldiers who had sustained battlefield wounds. Both osteotomies have gone on to union. One plate has broken, requiring exchange for an intramedullary rod, and both of the distal tibial corrective osteotomies have united but only after considerable time. One of these, a rotational and lengthening osteotomy, required 4 months of exogen to ensure union.

11.1.4 Conclusion

3D planned and printed osteotomy is now an established methodology. By investing in detailed planning, the intraoperative process is simplified substantially, and the clinical outcomes are encouraging. The project has enabled some very complex reconstructions, and by automation, the time taken to produce a plan has fallen steadily.

11.2 Minimally Invasive Osteotomies Around the Knee

11.2.1 Introduction/Historical Background

Osteoarthritis is a very common cause of knee pain. It affects high percentages of patients above 60 years of age [5] but is also seen in younger patients as a result of different etiologies including rheumatoid arthritis, a genetic predisposition, poor cartilage quality, or obesity.

In addition, mechanical malalignment is widely accepted as a major source of osteoarthritis. Numerous studies have shown that at least 30% of the male population and almost 20% of the female population have a lower limb malalignment of more than 3° [5–7]. Regardless of the underlying cause of this malalignment, it then secondarily leads to high pressure loads and peak load areas resulting in mechanical abrasion. The patient then enters a vicious circle of progressive cartilage loss and worsening malalignment [8–11].

It is widely accepted that the best way of realigning and treating malalignment is with an osteotomy performed around the knee. Depending on the malalignment in the coronal plane, varus or valgus corrections can be achieved by open or closed-wedge osteotomies, which can be carried out laterally or medially at the level of the femur or tibia.

Regardless of the type of osteotomy, the aim is to correct the malalignment by changing the weight-bearing line and shift the peak load areas [12]. Recently, more attention was paid to the orientation of the joint line in relation to the Mikulicz line to restore the kinematic alignment profile [5, 13, 14]. To avoid creating a new deformity and malalignment of the joint line orientation, proper analysis is mandatory [15–17]. Having carried out the deformity analysis, it is not uncommon to find that there is a degree of deformity in both the distal femur and proximal tibia. And it is the experience of our unit and other centers [14] that the best results can be achieved by making the corrective realignment procedure at the level of the osteotomy. That, in many cases, is in both the distal femur and the proximal tibia with a double osteotomy. Though newer techniques of high tibial osteotomies (HTO) led to superior results, HTO and distal femoral osteotomy (DFO) are still considered to be difficult procedures with high potential risk in terms of complications [18, 19]. In the case of HTO, the number of recent outcome papers is low, and these are mostly based on historical techniques with relatively poor outcome long term [20, 21]. Again, in DFO surgery the procedure is considered technically challenging with higher complication rates, although a meta-analysis did not reveal supporting evidence [22].

It is now widely accepted that there is at least a 20% dissatisfaction rate with total knee replacement (TKR) surgery. There are also limitations of what can be achieved with a TKR, and we always need to have a plan “B” in the event of failure and think about the next procedure in an ever-aging population with high demands. In spite of this, this procedure is increasingly performed [23]. Paradoxically, osteotomy yields excellent results [19, 24, 25]; however the number of osteotomies carried out is decreasing. This could be explained by the feeling that these procedures are considered to be difficult and high risk. Furthermore, the shift to joint replacement surgeries over the last decades has been encouraged by the industry, and at the same time, we have seen relatively few centers of excellence and training initiatives for osteotomy surgery.

Taking that into consideration, there has been a need to adopt the recent major advantages of osteotomies around the knee and simplify the procedures to make them more reproducible and less traumatic.

11.2.2 State-of-the-Art Treatment/Biomechanical Problems HTO and DFO

One of the problems in a review of the literature of osteotomy surgery is the vast number of heterogeneous treatments and techniques that have been reported. As a result, there is a strong need to define a surgical standard that needs to be reproducible in terms of indication, planning, execution, and teaching. At the moment, the only standardized teaching and techniques to meet these criteria for osteotomy are those recommended by the Joint Preservation Expert Group (JPEG) of AO.

Correcting the tibia is achieved by medial open or closed-wedge technique for valgus or varus deformity. The more reproducible and accurate approach for high tibial osteotomy surgery is to carry out a medial opening wedge procedure of the proximal tibia. Unlike the lateral closing wedge technique, where there is a risk of common peroneal nerve injury, a need to perform a fibula osteotomy and more soft tissue dissection to the lateral compartment, the medial approach involves minimal soft tissue dissection, significantly less risk of neurovascular damage, and the open wedge approach allows "fine-tuning" of the osteotomy [26, 27].

For femoral malalignments, routinely closed-wedge osteotomies (either medially or laterally) are performed to correct coronal plane deformities. The distal femur shows different biomechanics than the proximal tibia. The surface at the level of the osteotomy is smaller on the femoral side. There is no natural "hinge-preserver" such as the fibers of the proximal tibiofibular joint in the area of the safe zone [28, 29], and the lever arm of the DFO is longer. As a result, DFO is inherently more unstable. To help with this problem of potential instability, we recommend, as a routine, that a proximal biplane second cut is made to provide more stability and also to help with the healing process [30, 31].

The biplanar technique for DFO and HTO (Fig. 11.5) has numerous advantages. Geometrically the volume of the osteotomy is reduced, the osteotomy can be performed closer to the metaphysis with better bone healing, and there is an inherent higher axial stability, protection against the potential issue of malrotation, and an option for reduction in case of a hinge fracture [27, 30, 31].

These biplanar techniques, along with angle-stable plate fixators, reproducibly showed very good midterm results and patient satisfaction [19, 32, 33]. A further technical advancement has been the introduction of a minimally invasive (MIS) approach to both, the proximal tibia and distal femur, which has been the standard in our department for the last 2 years.

11.2.3 MIS Technique/Future Options

The MIS biplanar technique we have developed is less invasive but still allows the procedures to be carried out safely in experienced hands. The key is to make the incision at the right location to allow optimal visualization (Fig. 11.6). This incision allows a window to be created, and like any MIS technique, this window is moved as is required. With increasing surgical experience in osteotomy surgery, it is possible to bring down

Fig. 11.5 Biplanar osteotomy at the distal femur (DFO) and the proximal tibia (HTO)

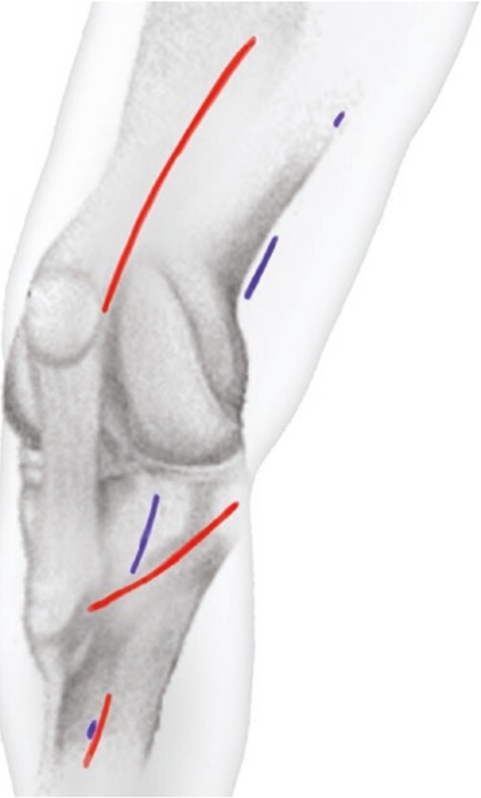

Fig. 11.6 Incisions for conventional (red) and MIS (blue) technique

the incisions to less than 4 cm for DFO and HTO. We do not advocate this technique for less experienced osteotomy surgeons at the start of their learning curve and would suggest a stepwise progression toward the MIS technique as the surgeon gains experience and confidence.

MIS in medial open wedge HTO is linked to the incision length. As there is no critical structure in the approach up to the MCL, MIS doesn't help to reduce the surgical trauma. But taking into consideration that osteotomy patients undergo revision surgery, the surgical pathways need to be planned thoughtfully. The skin bridge between two proximal tibial incisions should at least be 5 cm [34]. An incision shorter than that can be considered noncritical. Substantial change with the MIS approach is the direction of the incision, which at the distal end is medial to the tibial tubercle and goes slightly obliquely to the level of joint line and no longer to the posteromedial corner. The two osteotomy cuts need to be performed sequentially in a window-shift technique so as the placement of the drill sleeves being used for the plate fixator in the proximal part. The shaft screws are placed through a single-stab incision.

For the DFO procedure, the MIS approach moved significantly from a long median incision to a medial or lateral 4 cm incision at approximately 4 cm above the epicondyles. At the medial side, the fascia of the vastus medialis is then incised and longitudinally split. Blunt dissection around the muscle is performed to the dorsal circumference. At the lateral aspect, the upper border of the iliotibial band needs to be identified and divided in a longitudinal way. Care is to be taken at the distal parts around the vastus lateralis as branches of the lateral ascending genicular artery penetrate the intermuscular septum. These either need to be ligated or coagulated. From there, it is possible to lift the vastus medialis or lateralis to gain access to the medial or lateral intermuscular septum, which is then incised close to the femur. The key is to dissect the posterior aspect of the femur. That has to be revealed, and this can be done minimally invasively without lifting the whole muscles at each side. By doing so, there is minimal compromise to the vascularity of the area. It has been shown that conventional plating, when compared to MIPO (minimal invasive plate osteosynthesis), causes limitations for periosteal and bone marrow perfusion, leading to compromised osteotomy consolidation [35–37]. Performing the osteotomy and applying the plate like in HTO is achieved by window shifting. The placement of the shaft screws is also done by stab incision. To establish a safe portal with limited damage to the muscle, a cannula is placed in the stab incision. Following these MIS principles, in our hands surgical trauma has been reduced. Following deformity analysis, we have found significant numbers of varus patients with femoral deformity. Up to 20% of our varus deformities are located in the distal femur and are treated by lateral closing wedge DFO surgery. In conclusion, femoral osteotomy procedures are currently not carried out in sufficient numbers. Where appropriate, osteotomy needs to be performed in the femur and not always carried out in the tibia for varus deformity. The same is true in valgus deformity, where a significant number of patients have a deformity in the tibia as opposed to the femur, and therefore this is where the osteotomy should be carried out to prevent the procedure from creating an oblique joint line and a new deformity. In recent times, attention has been paid to the orientation of the joint line, along with the postoperative correction of the weight-bearing line [5, 14, 38]. From a dynamic perspective, the knee medializes during gait. This leads to a horizontal joint line orientation, when the joint line is medially inclined in stance. As a consequence, altering the MPTA to abnormal values to correct the weight-bearing line might lead to disturbed kinematics. Though at present there is no scientific evidence, our threshold for a postoperative MPTA is 93°. It is important to understand that the femur is decisive for joint line orientation. If the desired correction cannot be achieved within reasonable values for mLDFA and/or MPTA, we tend to plan a DLO (double-level osteotomy).

11.2.4 Take-Home Message

Biplanar osteotomy with angle-stable plate fixators produces excellent results when carried out for the right indications. As our understanding of malalignment, planning and execution of osteotomy surgery has evolved, the vast majority of the technical challenges of the past have been largely solved. Having said that, this field will continue to develop and improve with time. These interesting new concepts of correction philosophies have led to controversial discussion over the last years and led to promising concepts such as the MIS technique and focus on joint line orientation. The big challenge of the next decades will be to bring osteotomy back to a broader surgical society and to establish these working concepts as standard treatment pathways.

11.3 Intra-articular Osteotomies

11.3.1 Introduction/Historical Background

Osteotomy around the knee was traditionally focused on metaphyseal corrections, mainly treating deformities in the frontal plane. Indications for intra-articular osteotomy may be unilateral constitutional deformity, posttraumatic intra-articular deformity (Fig. 11.7), and unilateral deformity induced by osteoarthritis. Intra-articular osteotomies may be performed by hemiplateau osteotomy (wedge type, Chiba type) and by plateau osteotomy.

11.3.2 State-of-the-Art Treatment

11.3.2.1 Constitutional Deformities

Constitutional deformities suitable for intra-articular osteotomy are Blount disease, Ellis-van Creveld syndrome, and also some types of achondroplasia. In all these conditions, one tibia plateau will be depressed or angulated, causing significant axial deformity of the leg. Normal anatomy can be restored by the technique of hemiplateau osteotomy (Fig. 11.8). An osteotomy plane is created under the involved compartment with the hinge point at the borderline to the intact part of the tibia plateau. A wedge-type fragment is thus created, and by opening the osteotomy plane, correction is achieved. The gap is usually filled with an autologous bone graft from the iliac crest, and fixation is achieved by a locking plate [39].

The technique of open wedge hemiplateau osteotomy allows to restore the joint line but does not interfere with any metaphyseal deformity the patient may have in addition. In this case, the intra-articular osteotomy may be combined with a typical extra-articular osteotomy in the metaphyseal area, or the correction has to be planned in two stages [40].

11.3.2.2 Posttraumatic Intra-articular Deformities

Intra-articular Osteotomy

Intra-articular fractures may result in malunions, and intra-articular deformities are commonly seen after tibial plateau fracture treatment. A certain percentage of cases may be suitable for hemiplateau osteotomy. However, the defect of the joint surface may be irregularly shaped due to depressed osteochondral fragments. In this situation, a direct intra-articular osteotomy may be used, elevating

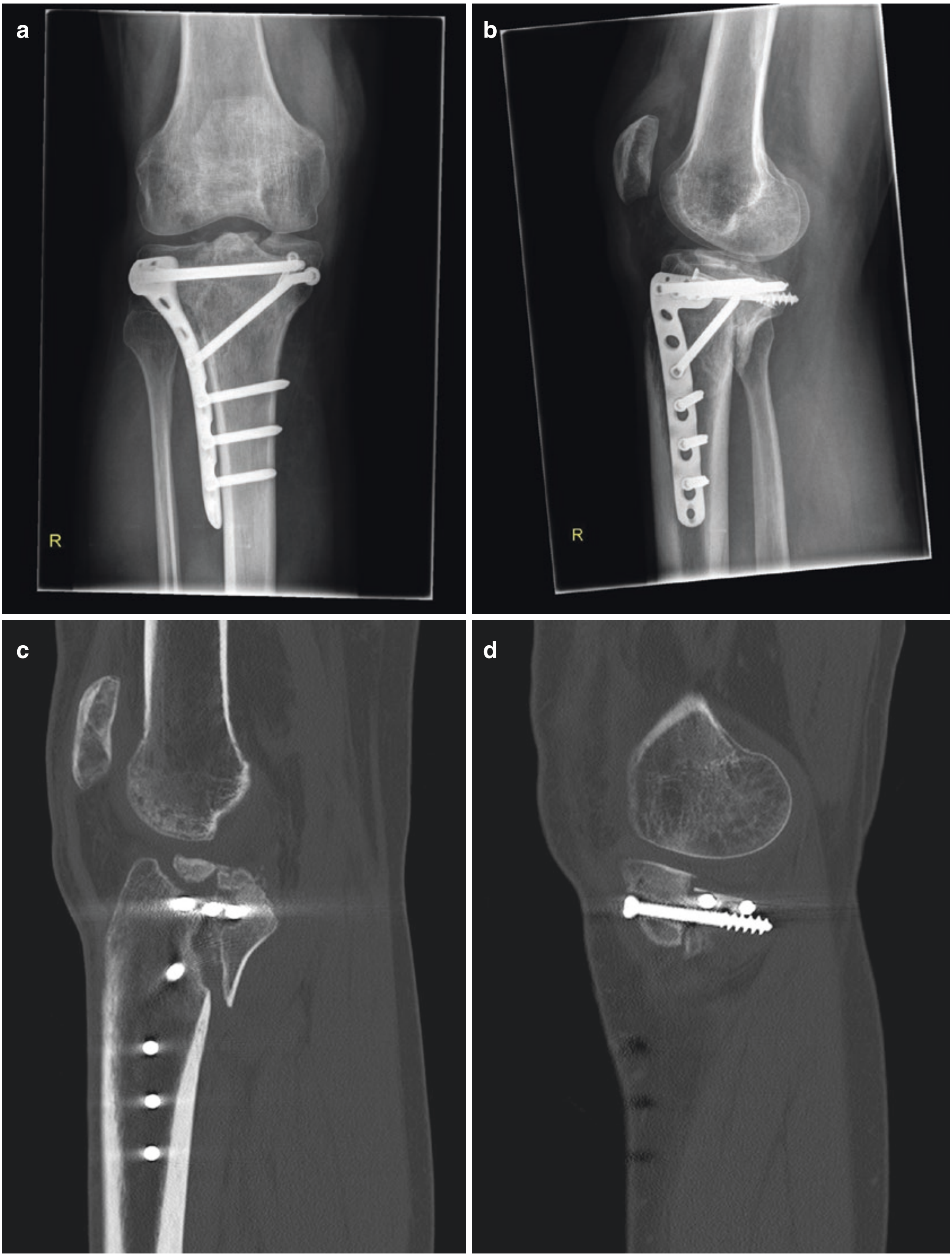

Fig. 11.7 (**a**–**h**) Intra-articular osteotomy. The images show a 34-year old patient after ORIF of bicondylar tibial plateau fracture (**a** and **b**). At 8 months, CT reveals a pseudarthrosis (**c**), with an articular step of 1 cm (**d**). Treatment included removal of medial hardware, mobilization of the pseudarthrosis (prone position, posteromedial approach), open reduction, fixation with posterior plate, and use of autologous bone graft from the posterior iliac crest. Postoperative radiographs (**e** and **f**) and after 9 months (**g** and **h**) are shown. The patient is now pain-free and is able to go mountain hiking without problems

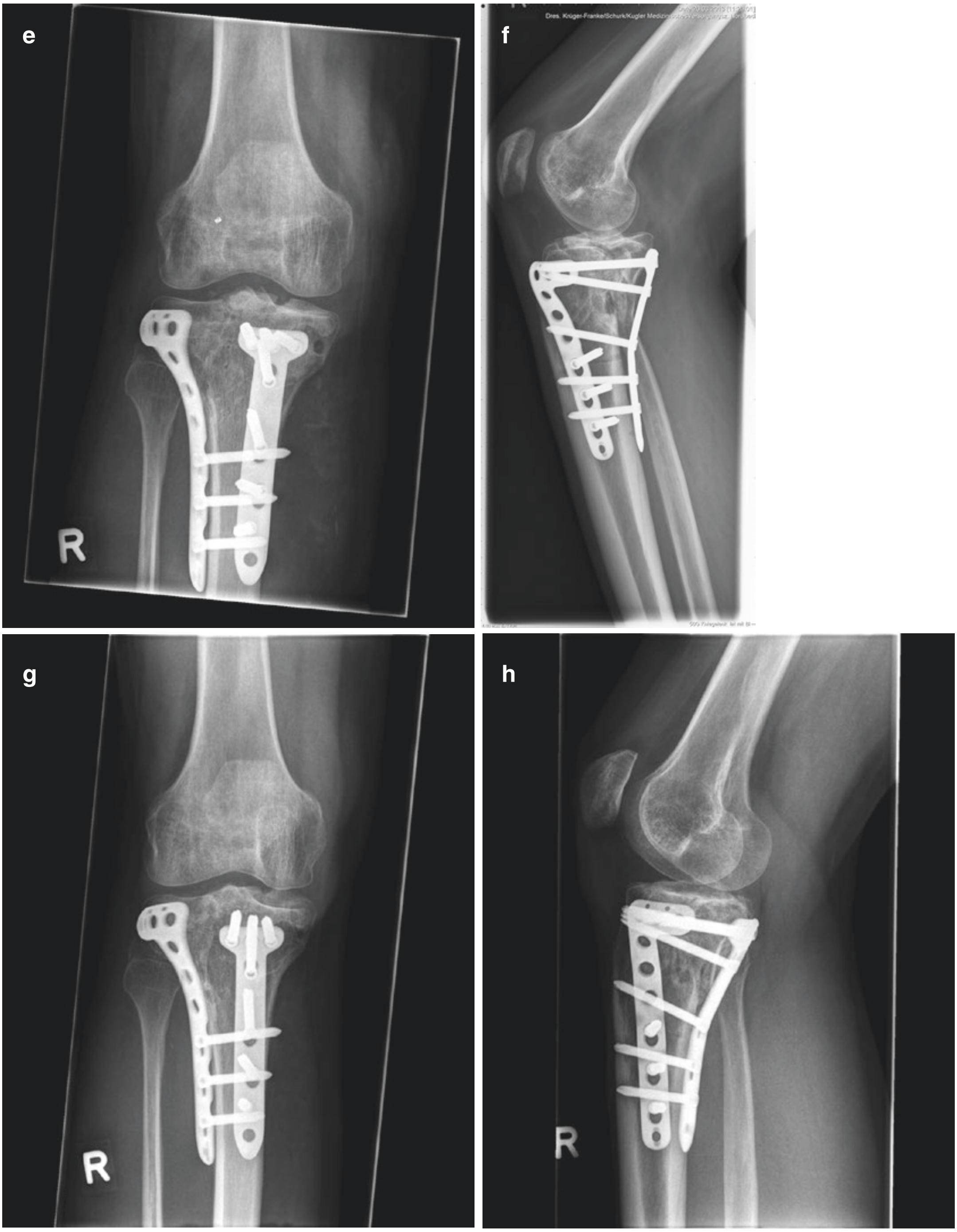

Fig. 11.7 (continued)

the depressed fragments and thus recreating the initial fracture situation. A specific extended exposure of the tibia plateau is mandatory to allow the surgeon to work under direct vision, and autologous bone grafts as well as locking plates are used to support the elevated areas. Again, this intervention can be combined with a metaphyseal osteotomy to correct an additional deformity [40].

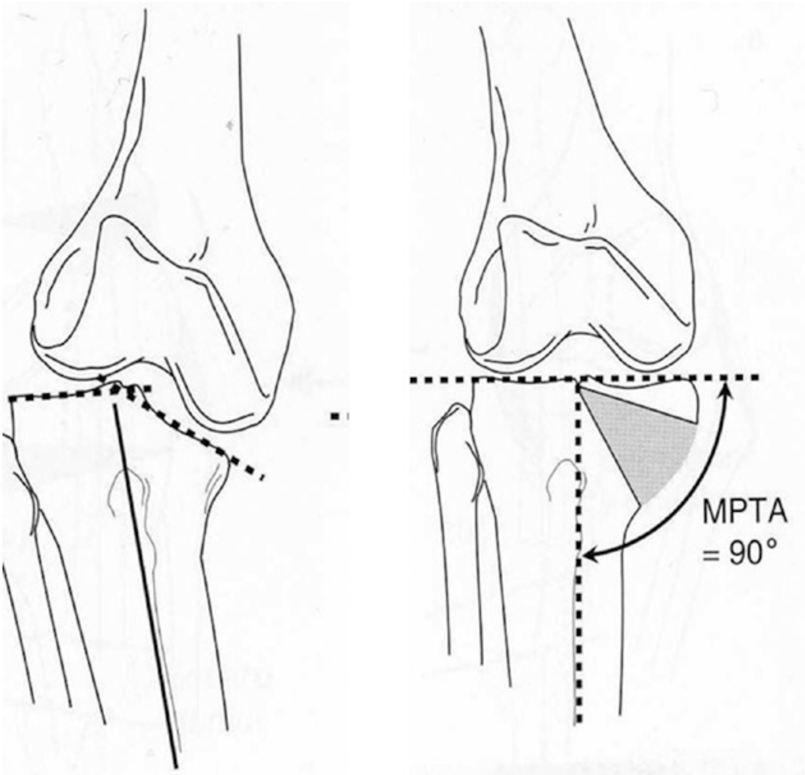

Fig. 11.8 Principle of hemiplateau osteotomy

Osteochondral Grafting and Metaphyseal Osteotomy

Open reduction and internal fixation may lead to necrosis of the osteochondral areas involved. In these defect situations, a reconstruction with local tissue is not possible any more. Fresh solid allogenic osteochondral grafts can be used to substitute for the defect if available. Such grafts are not available in our country, and we use a shaped cortico-cancellous graft from the iliac crest instead. The periosteal part of this graft faces the joint cleft. This graft is shaped individually to the defect for press fit; residual defects are filled with cancellous bone grafts. A locking plate can be used to support the graft by rafting screws. The overall alignment in the frontal plane has to be corrected, and any overload of the graft requires an additional metaphyseal osteotomy.

Intra-articular Osteotomy for Osteoarthritis of the Knee

Metaphyseal osteotomy around the knee is not recommended for patients with normal long bone configuration but gross intra-articular defects. An extra-articular correction of alignment will lead to an abnormal orientation of the joint line, creating shear stress on the cartilage. However, by elevating the involved side, the instability of the joint and the imbalance may be eliminated. This concept of intra-articular osteotomy in osteoarthritis was developed in Japan by Chiba (TCVO, tibia condylar valgus osteotomy) (Fig. 11.9). Medium-term results show patient benefit at a level of arthroplasty [39].

11.3.3 Future Treatment Options

Advanced digitizing and modelling technology will be helpful in planning of intra-articular osteotomies. PSI techniques will allow for individualized osteotomies based on advanced planning programs. Robotic technology may aid the surgeon to make individual grafts for large defects.

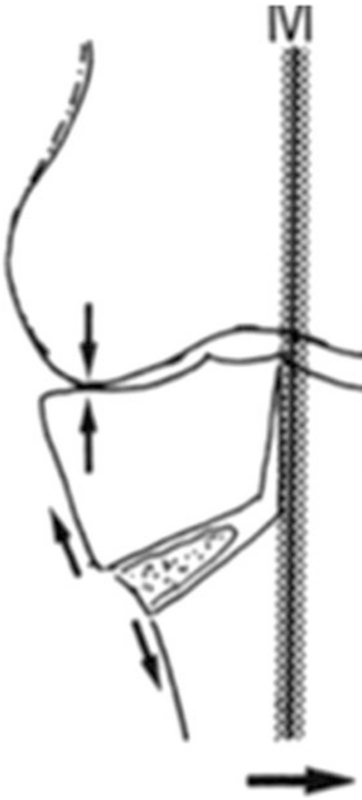

Fig. 11.9 Principle of tibial condylar valgus osteotomy (TCVO/Chiba)

11.3.4 Take-Home Message

Preservation of the knee joint is possible in many cases of intra-articular defects or posttraumatic malunion. The clinical results in appropriate selection are superior compared with arthroplasty which has a significant risk profile. Key points are restoration of the joint line and correction of any frontal plane deformity causing overload of the involved compartment.

11.4 Osteotomies for the Cruciate Deficient Knee

11.4.1 Anatomy and Biomechanics of Slope

In addition to stability imparted by ligamentous and soft tissue structures about the knee, the tibiofemoral joint articular surfaces contribute significantly to stability of the knee joint. In addition to coronal alignment, posterior tibial slope (PTS) plays a critical role in both the sagittal and rotational stability of the knee.

Generally, tibial slope is measured on the lateral radiograph and is defined as the angle between a line drawn parallel to the tibial plateau and a line along the longitudinal axis of the tibial. Conventionally, the line is drawn along the medial tibial plateau, but it is becoming more evident that the lateral tibial plateau slope is critical to the kinematics of the knee as well.

A wide range of tibial slope has been proposed in the literature. Although tibial slope varies between individuals, posterior tibial slope is generally accepted to be within the range from 6° to 11° in the sagittal plane, and it is generally believed to be pathologic if it is ≥12° [41–43]. This slope results in a shear force when compressive load is passed through the joint, which results in an anterior translation moment of the tibia relative to the femur [44, 45]. This anterior shift tends to be most pronounced with the knee in full extension and decreases with flexion of the knee. Furthermore, axial compressive load results in a proximal and anterior force, as a result of posterior tibial slope [46].

Osteotomy shifts the contact pressures and resting position of the tibia with respect to the femur, with an increase in the slope moving the resting point posterior and a decrease in the slope moving the point anterior. Thus, these changes can help biomechanically overcome PCL- and ACL-deficient knees, respectively [46]. While altering the slope in a ligament-intact knee may not significantly alter contact pressure of the femur on the tibia, altering tibial slope in a ligament-deficient knee can significantly increase the contact pressure of the knee. An increase in tibial slope of 5.5° will move the contact pressure up to 24% posteriorly [47].

11.4.2 High Tibial Osteotomy for the ACL-Deficient Knee

While the anterior cruciate ligament (ACL) is the main restraint to anterior translation of the tibia, malalignment of the extremity can leave an individual susceptible to ACL injury, as well as affect the stability of the ACL-deficient knee. Two patterns particularly exacerbate instability, as well as the rate of arthritic change in the ACL-deficient knee: osseous varus malalignment with medial compartment wear and increased tibial slope [48].

Increased tibial slope of both the medial and lateral plateaus has been shown to be a significant risk factor for ACL ruptures [49–55]. In conjunction with a natural posterior slope to the tibial plateau, the absence of the ACL results in anterior translation of the tibia with respect to the femur [56]. However, altering the tibial slope significantly changes the amount of anterior translation of the femur [46], with every 10° increase in posterior slope being associated with between a 3–6 mm increase in anterior translation of the tibia [44] and an increase of 4–5° resulting in a 2–3 mm increase in anterior translation [46].

Posterior tibial slope also appears to play a role in the rotational stability of the knee. Increased tibial slope is associated with increased Lachman and higher-grade pivot shift testing, and decreasing the slope is associated with increased rotational stability of the knee with decreased grade pivot shift, but no change in Lachman test [57, 58].

In conjunction with being intimately related to the stability of the knee, increased tibial slope ≥13° also puts increased stress on the medial compartment and leads to an increased risk of medial meniscus tears in the context of an ACL-deficient knee [59].

When comparing lateral closing-wedge (LCW) with medial opening-wedge (MOW) HTO in the ACL-deficient knee, LCW has shown to more reproducibly neutralize the posterior tibial slope and decrease anterior tibial translation in the context of ACL-deficiency, and, although it can also more often be associated with external tibial rotation and lateral patellar tilt, it may more significantly alter patellofemoral mechanics [60].

Generally, in ACL-deficient knees with varus alignment deformities, single-stage ACL reconstruction and HTO has demonstrated to be a reliable operation with good to excellent outcomes at long-term follow-up [61–63]. However, others argue that it may be prudent to stage HTO first and only perform the second stage of ACL reconstruction 6–12 months following surgery if instability persists. Especially in older patients, HTO alone can be an excellent, reproducible treatment option [64].

11.4.3 Deflexion Osteotomy for ACL Without Coronal Adjustment (Dejour)

There may be a role of HTO in the setting of appropriate coronal alignment of the knee. Dejour et al. recommend considering a deflexion osteotomy without coronal plane adjustment for patients with two or more failed ACL reconstructions and a pathologic tibial slope (generally ≥12°). In order to perform this technique, an anterior longitudinal incision is made just medial to the tibial tuberosity, with elevation of the soft tissues posterior to Gerdy's tubercle. Osteotomy is recommended from the superior margin of the patellar tendon insertion and directed in an inferior direction, in order to avoid involving the tibial tubercle in the osteotomy. A second cut is made parallel to the joint line up to the posterior tibial cortex, which is then wedged for a goal slope of between 3° and 5° distally, with 1 mm of opening being equivalent to 1° of slope. Excellent results were reported at 4 years in conjunction with ACL reconstruction, with no revisions required and no postoperative complications, and only two of nine patients develop worsening in osteoarthritis at final follow-up [41]. An anterior closing wedge osteotomy, which involves the tibial tubercle, is also described. Although PTS was only improved from 13.6° preoperatively and 9.2° postoperatively in their series, they report excellent clinical outcomes at final follow-up [65].

11.4.4 High Tibial Osteotomy for the PCL-Deficient Knee

While decreasing the tibial slope can help improve the position of the tibiofemoral joint in the ACL-deficient knee, the converse is true in the PCL-deficient knee. Patients with PCL deficiency lack a restraint to posterior translation of the tibia on the femur. The degree of sag is related to the grade of PCL lesion, with grade I being 1–5 mm, grade II being 5–10 mm, and grade III being >10 mm. With loading, the change in resting position results in abnormal kinematics at the knee joint, which, over time, leads to increased strain and injury to the meniscus and wear due to higher contact pressures, especially in the anterior medial compartment [66, 67]. Furthermore, the posterior sag of the tibia can also result in osteoarthritic changes in the patellofemoral joint, particularly the lateral facet, with contact pressures in this joint increasing up to 16% [67].

PCL deficiency results in a posterior shift of the tibial resting position of about 8.4 mm at 90° flexion compared with a normal knee [68], which clinically manifests as posterior sag. However, slope altering osteotomy can help normalize contact pressures. By increasing the tibial slope from 9° to 14°, resting position is moved anteriorly 4 mm at 90° flexion and moves further anteriorly with axial compressive load [68]. As a result, load is transferred in a more anatomic nature with increased slope in the PCL-deficient knee, despite the absence of ligamentous stability.

Traditionally, closing wedge lateral HTO and dome osteotomies are thought to provide minimal opportunity to decrease the tibial slope [69], so medial opening wedge high tibial osteotomy has become the mainstay of treatment for PCL-deficient knees. The degree of correction in the sagittal plan can be evaluated by measuring the gap created by the osteotomy. It is important to consider that the shape of the proximal anteromedial tibia cortex is triangular and intersects the posterior cortex at about 45°, while the lateral tibial cortex is nearly perpendicular to the posterior tibia. As a result, an equal anterior and posterior osteotomy gap results in an increased slope, while slope does not change if the anterior gap is smaller than posterior [70]. Thus, for every 1 mm increase in the anterior gap, the posterior slope increases by about 2° [71].

Opening wedge HTO in the varus PCL-deficient knee has been shown to provide good clinical outcomes. Generally, the recommendation for varus PCL-deficient knees is to perform the osteotomy alone and only proceed with ligamentous reconstruction after 6–8 months if there is continued instability following corrective osteotomy [72]. However, further long-term studies are needed to truly evaluate the relationship between this treatment method and prevention of the progression of osteoarthritis.

11.4.5 Double and Triple Varus Knee

In order to classify abnormalities of instability and alignment of the knee, Noyes et al. created the terminology for primary varus, double varus, and triple varus. Primary varus is simply the varus osseous anatomy of the tibiofemoral joint, such as occurs with medial meniscectomy or medial compartment degenerative wear. Double-varus alignment occurs with the combination of varus tibiofemoral osseous alignment in combination of insufficiency of the lateral soft tissues of the knee, including the posterolateral ligament complex. Triple varus of the knee occurs when increased external tibial external rotation and hyperextension of the knee (varus recurvatum) is found in conjunction with the varus osseous alignment of the knee and insufficiency of the lateral soft tissues. This is often found with a significant varus thrust with gait [73, 74]. Furthermore, chronic triple varus is often found in conjunction with medial compartment posteromedial wear, due to chronic anterior subluxation of the tibia [75].

Much like in the PCL-deficient knee, tibial slope plays a critical role in stability of the triple varus knee, but it may not fully restore rotational stability. The literature demonstrates that combined sectioning of the PCL and PLC results in a 10.5 mm increase in posterior drawer, 15.5 mm increase in dial test at 30°, and 14.5 mm increase in dial test at 90°. Increasing the posterior slope by 5° tends to reduce translation by about 3 mm but does not have a significant impact on rotational stability when assessed by dial testing [76].

In the case of double or triple varus, HTO should always be performed before ligamentous reconstruction, and consideration should be given to wait 6–8 months to reliably evaluate the degree of instability imparted by the soft tissue injury.

Long-term varus stress, the stretched lateral structures, and proper tensioning of the soft tissues require the changes to the osseous anatomy to be performed first [74].

11.4.6 Take-Home Points

1. Posterior tibial slope is generally accepted to be within the range from 6° to 11° in the sagittal plane, and it is generally believed to be pathologic if it is ≥12°.
2. High tibial osteotomy can be utilized effectively for management of the ACL-deficient knee, with or without ACL reconstruction. Care should be paid to the PTS, with slopes ≥12° being an indication for altering slope.
3. Opening wedge HTO is generally preferred for PCL-deficient knees, due to a favorable ability to increase tibial slope. Slope should be normalized, and with every 1 mm increase in the anterior gap, the posterior slope increases by about 2°.
4. PCL deficiency can be found in conjunction with PLC injuries resulting posterolateral instability, defined as triple varus (osseous varus, incompetence of lateral soft tissues, external rotation, and hyperextension due to absence of PCL).
5. In the absence of coronal deformity, sagittal correction of tibial slope with a deflexion osteotomy should be considered in multiple failed ACL reconstructions with pathologic tibial slope ≥12°.

11.5 Simultaneous Bilateral High Tibial Osteotomy With Early Full Weight-Bearing Exercise

Many patients with osteoarthritis of the knee have symmetrical involvement and thus require a bilateral operation. Commonly, two-stage high tibial osteotomy has been performed during the same or in separate hospitalizations. Although simultaneous bilateral total knee arthroplasty is a common procedure these days, there is little report of simultaneous bilateral HTO. Because bone union takes a long time after conventional closed-wedge HTO surgery, patients are restricted from weight bearing for an extended period. However, development of open wedge HTO (OWHTO) and hybrid closed-wedge HTO (hybrid HTO) realized simultaneous bilateral HTO safely. The advantages of an HTO simultaneously performed for both knees in one operation with a single administration of anesthesia include the shortening of the hospitalization period, reduced costs, and lower anesthetic risks. Optimal postoperative rehabilitation following simultaneous bilateral HTO also allows early full weight bearing without any support, which can prevent the aggravation of osteoporosis and dementia. In OWHTO, combination of using beta-tricalcium phosphate (β-TCP, porosity of 60%) wedges and angle-stable plate fixation improved initial stability [77]. In hybrid HTO, a novel technique and new plate system realized early full weight bearing [78].

11.5.1 Postoperative Rehabilitation

The day after surgery, all patients are permitted standing exercise with full weight bearing, range of motion, and also muscle strengthening exercises are started actively and passively. Two days after surgery, partial weight bearing starts with the use of parallel bars. One or 2 weeks after surgery, every patient is allowed full weight bearing with or without a small cane according to their knee pain. From 3 to 6 months after surgery, patients are permitted to engage in sports activities. However, in OWHTO, rehabilitation schedules will be changed if an unstable type of lateral hinge fracture happens during surgery.

11.6 Open Wedge High Tibial Osteotomy for Spontaneous Osteonecrosis of the Knee

Spontaneous osteonecrosis of the medial condyle of the knee (SONK) occurs often in middle-aged patients and appears unilaterally in the medial femoral condyle of the knee. The clinical presentation of SONK includes the sudden onset of acute severe pain in the knee, which generally worsens at night.

11.6.1 Surgical Technique

Intra-articular procedures were performed arthroscopically. Damaged cartilage tissue was removed completely, the SONK lesion was curetted, and drilling of the necrotic area with a Kirschner wire of 1.6 mm was then performed. After that, OWHTO is performed and fixed with an angle-stable plate [79].

11.6.2 Treatment for SONK

SONK is a rare disease of the adult knee that was first described by Albäck in 1968 [80]. Various causes have been proposed for this disease, including an insufficiency fracture, a microfracture of the subchondral bone, degeneration of the meniscus, and vascular insufficiency in the distal femoral condyle [81, 82]. However, the precise etiology remains unknown. The incidence of SONK is also unknown, but the involvement of the knee has been reported to be approximately 10%. The clinical manifestation of SONK commonly includes the sudden onset of acute and severe pain which is frequently worse during the night and at rest. The clinical symptoms of SONK present typically in middle-aged and elderly patients as mild synovitis, mild effusion, and a minimal loss of range of motion [83]. These symptoms can therefore be difficult to distinguish from intra-articular diseases such as OA and meniscal tears.

Treatments for SONK, including conservative therapies, have been developed and most involve surgery. Some clinicians have advocated joint-preserving surgical procedures, such as core decompression and arthroscopic debridement, and reported that these procedures were successful in the early stage (no condyle collapse, no osteoarthrosis). There are other treatment options, such as unicompartmental knee arthroplasty (UKA) and total knee arthroplasty (TKA) for patients with severe osteoarthritis (Koshino's stage IV).

Aglietti et al. have reported that, in a cohort of 31 knees with SONK treated by HTO, 87% of the patients had a satisfactory evaluation with an average follow-up period of more than 6 years and that the ideal postsurgical FTA is 170° (10° anatomical valgus) [81]. Koshino et al. have reported that bone grafting or drilling into the necrotic lesion is effective in promoting healing in cases of osteonecrosis and recommend that surgical treatment is most effective when undertaken prior to the onset of osteoarthritic changes [83].

SONK is an acute disease whereas OA is a chronic disorder. Hence, the normal function of the knee, including range of motion of the knee joint, is not impaired in patients suffering from SONK as opposed to cases of osteoarthritis. Maintenance of a good range of knee motion is one of the most important considerations following knee surgery. However, there are currently few reports that describe the range of motion of the knee and cartilage regeneration in detail after a joint preservation surgery, HTO, for the treatment of SONK.

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