# Complex Osteotomies of Tibial Plateau Malunions Using Computer-Assisted Planning and Patient-Specific Surgical Guides

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**Summary:** The accurate reduction of tibial plateau malunions can be challenging without guidance. In this work, we report on a novel technique that combines 3-dimensional computer-assisted planning with patient-specific surgical guides for improving reliability and accuracy of complex intraarticular corrective osteotomies. Preoperative planning based on 3-dimensional bone models was performed to simulate fragment mobilization and reduction in 3 cases. Surgical implementation of the preoperative plan using patient-specific cutting and reduction guides was evaluated; benefits and limitations of the approach were identified and discussed. The preliminary results are encouraging and show that complex, intraarticular corrective osteotomies can be accurately performed with this technique. For selective patients with complex malunions around the tibia plateau, this method might be an attractive option, with the potential to facilitate achieving the most accurate correction possible.

**Key Words:** osteotomy, patient-specific, surgical guide, malunion, tibia plateau fracture, knee

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## INTRODUCTION

The knee joint is one of the most critical weight-bearing regions in the lower extremity. As a consequence, fractures around the tibia plateau may significantly affect articular loading, stability, and even range of motion (ROM). The primary goal in treatment is anatomic reconstruction of the articular surface and the mechanical axis, aiming to restore function of the knee joint. Fractures can be treated conservatively for minimally displaced fragments, otherwise surgical management is recommended.[1–3] Well-established surgical techniques like open reduction and internal fixation (ORIF), external fixation, or arthroscopically assisted osteosynthesis can be chosen for this purpose.[2,4–13] However, operative management is challenging[14] and may be associated with malunion if reduction is imprecise.[3,15–17] Malunion can result in posttraumatic osteoarthritis and loss of function. Ultimately, salvage procedures such as total knee arthroplasty (TKA) or rarely knee arthrodesis may be necessary in an end-stage situation.[17]

An intraarticular corrective osteotomy, although being a complex intervention, may be a preferable treatment option for posttraumatic malunions.[15,18] In this procedure, the malunited fragment is osteotomized and reduced to its anatomically correct position according to a preoperative plan. However, exact quantification of intraarticular malunion is difficult with traditional imaging techniques because of the 3-dimensional (3D) nature of the deformity. It is even more challenging to exactly reproduce the preoperative objective during surgery. Although computer-assisted planning and guidance techniques are commonly used to support surgeons in performing TKA and high tibia osteotomies, the surgical correction of intraarticular posttraumatic malunions with such methods was so far not addressed. Oka et al[19] and Schweizer et al[20] demonstrated the feasibility of combining 3D computer-assisted planning with patient-specific guides for correcting complex intraarticular malunions of the distal radius. In their method, a 3D preoperative plan was created that relied on the mirrored contralateral extremity. Based on this plan, individualized rapid-prototyped guides were manufactured to precisely reproduce reduction in the surgery.

We have extended the surgical technique proposed by Schweizer et al[20] and report on our early experiences in operative treatment of posttraumatic intraarticular malunions of the proximal tibia.

## PREOPERATIVE PLANNING AND SURGICAL TECHNIQUE

The proposed approach relies on computer-assisted preoperative planning to quantify a malunion and the required reduction in 3D. As the contralateral tibia will be used as a 3D reconstruction template, it is required that the contralateral limb of the patient is asymptomatic without history of trauma or obvious malalignment. In a first step, 3D triangular surface models of the pathologic and contralateral normal tibia are generated. The bone models are extracted from computed tomography (CT) scans semiautomatically using

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the segmentation functionality of the Mimics software (Materialise, Leuven, Belgium): Intensity thresholding and region growing are applied for identifying the cortical bone layer and for separating the tibia from the surrounding bone anatomy, respectively.

Computer-assisted preoperative planning is performed on a standard personal computer using the custom-made software application CASPA (University Hospital Balgrist, Zurich, Switzerland). The 3D model of the contralateral tibia is mirrored and subsequently aligned to the pathologic model using a surface registration algorithm. As in similar approaches,[21] the iterative closest point method[22] is used to superimpose the undeformed regions of the bone surfaces (ie, the epiphyseal and meta/diaphyseal parts) in an automatic fashion by minimizing the quadratic distances between surface points.

Next, the fracture lines and articular step-off have to be assessed to create the osteotomy plane(s). Dependent on the pathology, either a single or a combination of multiple osteotomy planes (ie, curved cut) is required for mobilizing the fragment that must be reduced. After virtual mobilization, the anatomic correct position of the fragment was determined by aligning it to the reconstruction template. By doing so, the required reduction can be exactly quantified in 3D (ie, 3 degrees-of-freedom in translation and 3 degrees-of-freedom in rotation) as the relative transformation of the fragment from its initial to its reduced configuration. However, applying the so-obtained 3D measurements in the surgery to correct intraarticular malunion can be challenging.[20]

One possibility to facilitate this task is the use of patient-specific guides. The basic idea of such an approach is that a guide body is molded on the bone surface. The irregular bone surface around the osteotomy helps to uniquely identify the location on the bone where the guide has to be positioned. We have developed different guides for supporting cutting and reduction.

Dependent on the complexity of the osteotomy, 2 different types of cutting guides are applied. If only 1 planar cut is required, parallel K-wires (2-mm-diameter) are used to intraoperatively define the osteotomy plane. Preoperatively, virtual K-wires, represented by cylinders, are aligned on the osteotomy plane in the planning application (Fig. 1A). Based on the cylinders, a guide (*cutting guide type I*) with drill sleeves is designed to exactly set the K-wires on their planned position in the surgery (Fig. 1B). The osteotomy is subsequently performed by guiding the saw blade along the K-wires (Fig. 1C). A different technique[20] is applied for performing curved cuts: as depicted in Fig. 2, the basic idea of this approach is that the cut is coarsely defined by consecutively drilling holes that are spaced between 5 and 10 mm. The position and direction is defined by drill sleeves that are integrated in a guide (*cutting guide type II*). Afterward, the holes are connected with a cannulated chisel to complete the osteotomy.

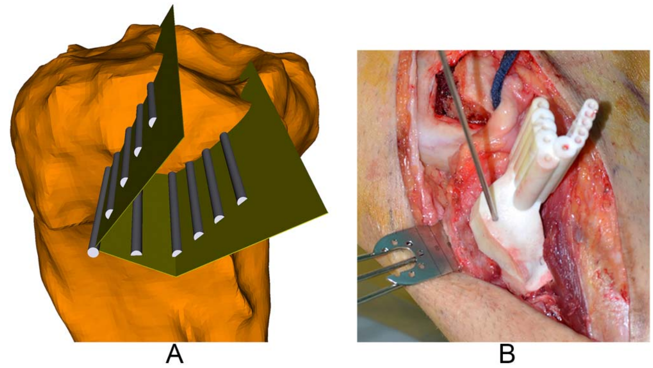


**FIGURE 2.** Guided complex-plane osteotomy. A, Virtual K-wires are aligned to the osteotomy planes in the 3D planning application. B, The cut is defined by consecutively drilling holes using a patient-specific guide. Afterward, the osteotomy is completed with a chisel.

In a similar fashion, K-wires are combined with guides to reproduce the 3D-planned reduction in the surgery. The general procedure for creating a reduction guide is illustrated in Fig. 3. First, cylinders representing 2-mm K-wires are created in the planning application (Fig. 3A). The cylinders are virtually fixed to the proximal and distal fragments. The corresponding drill sleeves to set the K-wires in the surgery are typically integrated into a cutting guide (Fig. 3B). A separate reduction guide is created based on the position and orientation of the cylinders after simulated reduction (Fig. 3C). It must be noted that such a guide must consist of 2 pluggable parts because the K-wires are divergent after reduction. After the osteotomy, the proximal and distal parts of the guide are slid along the K-wires (Fig. 3D). Thereafter, the parts are stably connected with a clicking mechanism to push the fragment to its anatomic correct position (Fig. 3E). After temporary fragment fixation using an additional K-wire, each part of the guide is separately removed, followed by fragment fixation with an osteosynthesis plate.

Based on the guide models provided as STL (Standard Tesselation Language) files, the guides used in the presented cases were produced by Medacta International S.A. (Castel

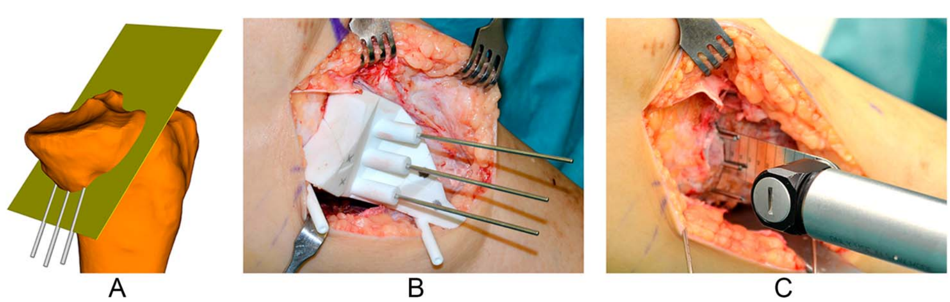


**FIGURE 1.** Guided single-plane osteotomy. A, Virtual K-wires are aligned to the osteotomy plane in the 3D planning application. B, Intraoperatively, the K-wires are set according to the planning using a patient-specific guide. C, The osteotomy is subsequently performed by guiding the saw blade along the K-wires.

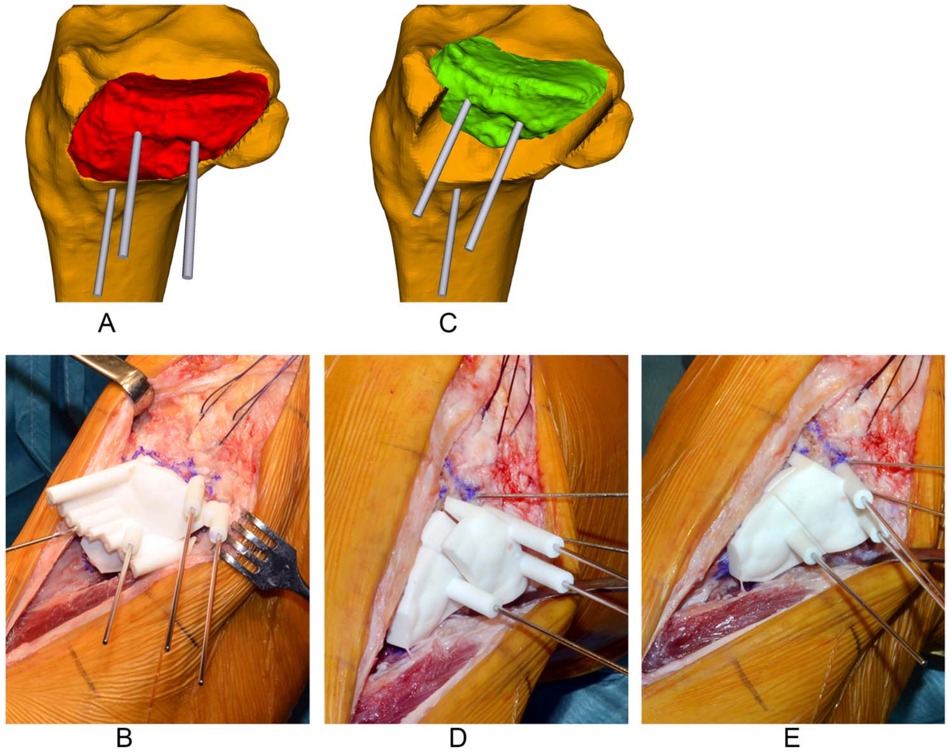


**FIGURE 3.** Patient-specific reduction guide. A, Virtual K-wires are created and fixed to the fragments. B, The corresponding drill sleeves are integrated into a cutting guide. C, Reduction is simulated, resulting in divergent K-wires. D, Reduction guide consisting of 2 pluggable parts. E, Reduction is completed by connecting the parts of the guide.

San Pietro, Switzerland) with a selective laser sintering technique based on polyamide PA-12. Sterilization was performed with conventional steam pressure at 130°C. It had been validated in laboratory experiments that no shrinkage can occur at this temperature.

## PATIENTS AND RESULTS

The proposed surgical technique was applied to 3 cases, characterized by an increasing level of complexity. Informed consent was obtained from all patients preoperatively regarding permission to report on their medical history and postoperative results. For each patient, preoperative assessment comprised of a long leg x-ray and bilateral CT scans (120 kV; axial resolution: 1 mm; Philips Brilliance 40 CT, Philips Healthcare, Best, the Netherlands) of the pathologic and the contralateral (normal) tibia. In all cases, a multiplanar malunion was confirmed by the 3D analysis (see **Table**, **Supplemental Digital Content 1**, http://links.lww.com/BOT/A300). The overall preoperative planning time including guide design was between 2 and 4 hours, depending on the case.

In case 1, a 32-year-old mason had sustained a bicondylar fracture (Schatzker type V, AO/OTA Classification[23] 41-C3) of the left tibial plateau that was conservatively treated (Fig. 4). The lateral tibial plateau healed in anatomic position, whereas the medial part dislocated progressively (Fig. 5A), resulting in a malunion and anteromedial pain. The patient was referred to our hospital considering corrective osteotomy 9 months after trauma. Physical examination revealed unrestricted ROM, tenderness at the medial joint line, and effusion. The knee was ligamentous stable. Surgery was performed 11 months after trauma with an anteromedial approach. The pes anserinus was only released in the proximal part. The superficial part of the medial collateral ligament was slightly detached anteriorly. An incomplete subchondral osteotomy was performed using a cutting guide (*type I*) and a surgical saw, followed by anatomic reduction which was guided as well.

In case 2, a 42-year-old painter sustained a multifragmentary fracture of the left tibia with a multipart fracture of the eminentia intercondylaris (Schatzker type II, AO/OTA Classification[23] 41-B3), treated by ORIF in a trauma center. However, the patient was never pain-free and was referred to our clinic 6 years later. Clinically, the medial compartment was still unremarkable with a negative varus stress test while the patient experienced pain with a substantial subluxation in the posterolateral defect of the tibia plateau during flexion. Effusion did occur but the knee was ligamentous stable and had unrestricted ROM. The 3D comparison with the contralateral tibia revealed a depression in the dorsal half of the lateral tibia plateau (see **Table**, **Supplemental Digital Content 1**, http://links.lww.com/BOT/A300; Fig. 5A). Four months after consultation, surgery was performed extending the former lateral approach. The posterior part of the tractus iliotibialis was released to expose the tuberculum Gerdy, which was used as a landmark for the guides. For better visualization of the posterior part of the joint, an osteotomy of the lateral femoral condyle was performed. Next, a cutting guide (*type I*) was applied and a first cut was performed from anterior with a surgical saw. Thereafter, the bone was accessed from the lateral side above the proximal tibiofibular joint to completely mobilize the fragment using 2 additional cutting guides (*type II*) and a chisel.

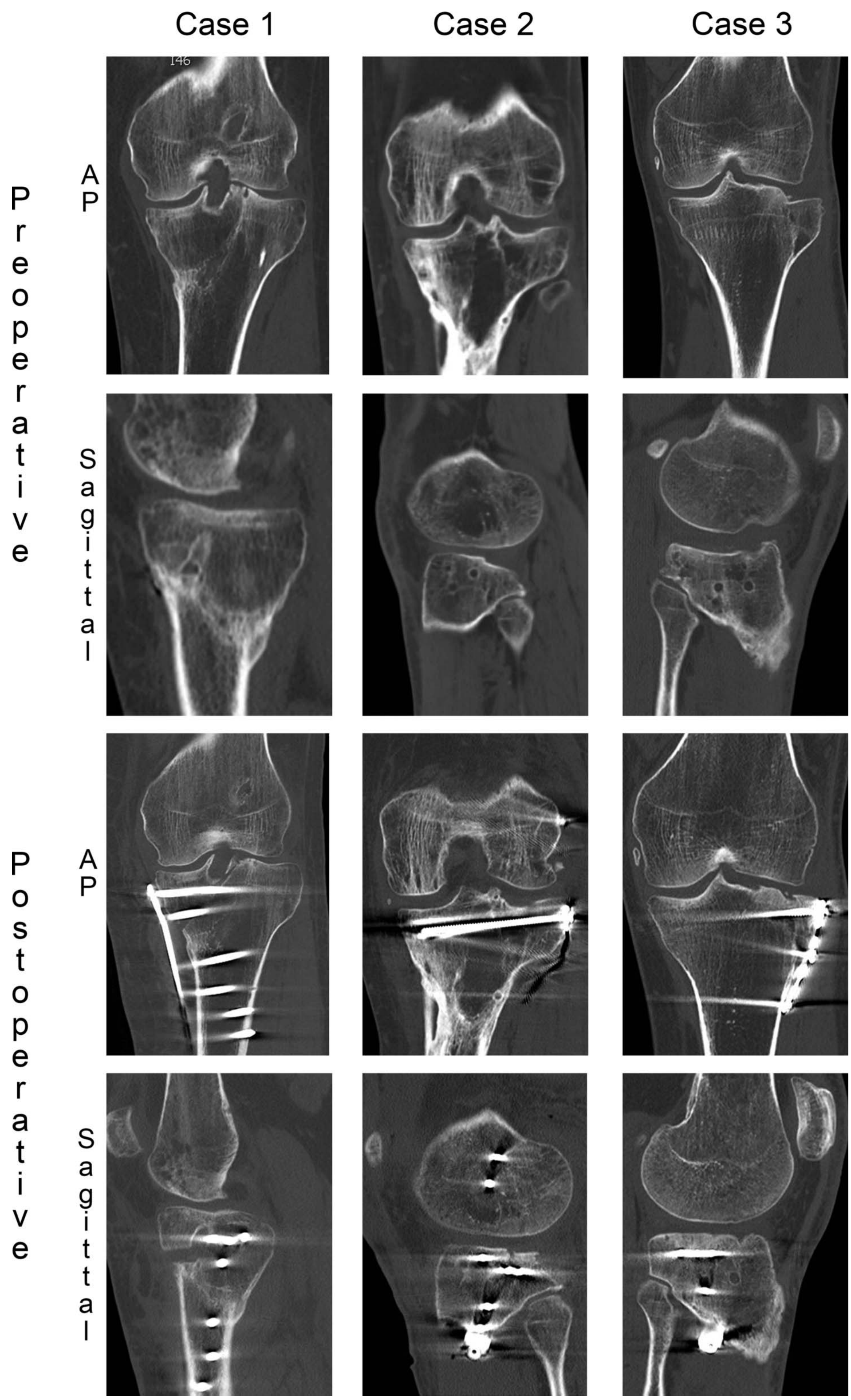


**FIGURE 4.** Computed tomography images of the presented cases are given before and after surgery.

In case 3, a 29-year-old engineer had a skiing accident, resulting in a split-depression fracture of the left lateral tibia plateau (Schatzker type II, AO/OTA[23] Classification 41-B3). The fracture was treated with ORIF in another institution. Sixteen months after trauma, the patient had a consultation in our hospital because of persistent pain and considerable

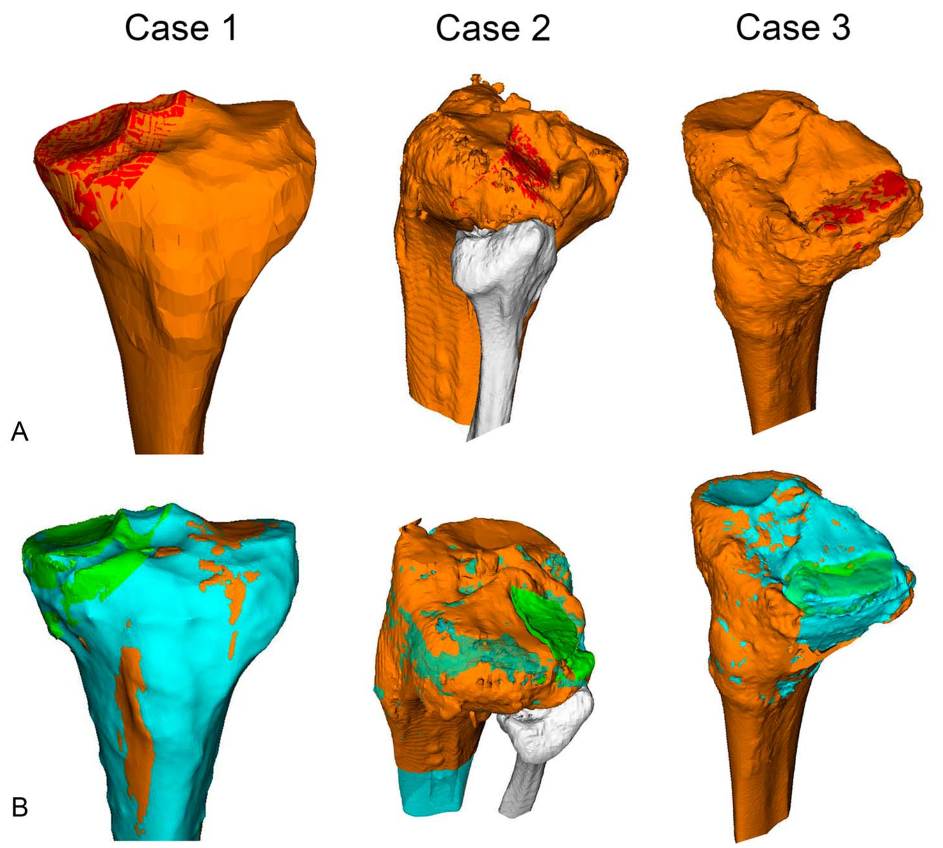


**FIGURE 5.** 3D computer-assisted planning and postoperative accuracy evaluation. A, Before surgery: the pathologic tibia is shown in brown and the fragment to be mobilized is outlined in red. B, After surgery: postoperative tibia (in light blue) compared with planned reduction (in green).

functional impairment. Evaluation showed a malunion of the biggest lateral fragment (see **Table**, **Supplemental Digital Content 1**, http://links.lww.com/BOT/A300; Fig. 5A) with already degenerative changes of the surrounding cartilage. Because of the young age of the patient, a corrective osteotomy was our preferable surgical treatment. Surgery was performed 22 months after trauma. The bone was accessed from anterolateral, and soft tissue was removed from the lateral tibial head. Two cutting guides (*type II*) were applied in combination with a cannulated chisel. One guide was used to mobilize the fragment as planned, and the other was required to remove an additional bone wedge. Thereafter, the 2-part reduction guide permitted correction of the multiplanar deformity.

In all cases, the fit of the guides seemed to be stable and well-defined. The postoperative course was uneventful. Radiologic examination showed that all osteotomies healed in between 3 and 6 months after surgery. The minimum follow-up time was between 12 and 14 months. A quantitative evaluation of the reduction error based on postoperative CT is given in **Supplemental Digital Content 1** (see **Table**, http://links.lww.com/BOT/A300). The residual error was assessed by comparing the preoperative planning result with the 3D model of the postoperative tibia (Fig. 5B). In cases 1 and 3, no limitation of the ROM was observed and there was no evidence of effusion. These 2 patients were very satisfied with the outcome and continued their former job (case 3) or pursued another job (case 1). In case 2, the osteotomy was not entirely performed as planned because the fragment could not be mobilized completely to achieve the planned position. However, failure to mobilize the fragment was not a failure of the system but of the execution of the procedure. Reason for the incomplete mobilization was missing guidance of the chisel in the medial part. Six months postoperatively, this patient improved in terms of posterolateral pain and subluxation but medial pain increased slightly because of the underlying varus osteoarthritis. ROM was not limited, but effusion was still present. The patient was not able to continue his former job, primarily caused by pain in the (untreated) medial part of the knee.

## DISCUSSION

In this report, we described a novel technique for performing complex intraarticular corrective osteotomies using 3D computer-assisted planning combined with patient-specific surgical guides.

Surgical treatment of tibial plateau fractures remains challenging[24] and may be associated with severe complication such as malunion or posttraumatic gonarthrosis.[3,25] Therefore, a corrective osteotomy may be indicated in young adults to decrease risk of gonarthrosis.[3,8,26] Studies[3,15,27,28] emphasized the importance of preoperative planning for exact quantification of malunions. Several authors proposed to use 3D-reconstructed CT to improve assessment of the deformity,[15,26,29] although still relying on preoperative planning based on 2D radiographs. Mast[27] was one of the first reporting on the use of the contralateral healthy tibia as a 2D reconstruction template for unilateral shaft malunions. More recently, 3D surface models of the contralateral bone have been used as reconstruction templates for the preoperative planning of corrective shaft osteotomies of the lower extremities,[30] as well as for extraarticular[31–33] and intraarticular[19,20] osteotomies of the upper extremities. In these studies, patient-specific guides were applied to accurately reproduce preoperative planning during surgery. Guides or navigation systems were also used in the other types of interventions around the knee to support the surgeon in performing tibial plateau fracture reduction,[34] high tibia osteotomies,[35–42] or TKA.[43,44]

We presented a computer-assisted surgical technique that has been initially applied to the distal radius articulation.[20] The proposed approach permitted accurate multiplanar reduction of 3D deformities. Moreover, it was even possible to perform complex curved cuts: in cases 2 and 3, a multiplanar closing wedge osteotomy was performed that required preoperatively calculating the exact 3D shape of the wedge to be removed. For completion of such types of osteotomies, the use of a cannulated chisel is suggested to prevent technical errors, which may lead to an incomplete mobilization of the fragment, as observed in case 2. In this case, not even the reduction of the mobilized part was satisfactory (ie, above 4 degrees residual error), because the repositioning relied only on manual alignment of congruent osteotomy surfaces. Therefore, we have further developed the design of the intraarticular guides combining the cutting guides with reduction guides, as demonstrated for cases 1 and 3. In these patients, the accuracy of the reduction was within 1 mm and 1.8 degrees. These results are promising compared with other studies, which either were more inaccurate[20] or had similar accuracy under laboratory conditions.[45]

The study and its proposed surgical technique had several limitations. First, the method was only applied to a small number of patients. Clinical scores were not evaluated because a focus was laid on first describing the surgical technique and measuring its accuracy. As the type of procedure may always remain very selective, being only feasible for a few qualifying patients, it was important for us to report first experiences to the community. This may help assessing advantages and drawbacks of this technology and to decide whether it would be worthwhile to pursue further development. Moreover, an additional CT would be required if the contralateral side is used as a reconstruction template, resulting in increased radiation exposure. On the contrary, the technique may reduce total fluoroscopy time during surgery. Lastly, additional expenses for guide manufacturing of approximately €250 (US $340) arise per case.

In conclusion, the presented technique enabled us to perform complex intraarticular osteotomies in a controlled fashion, restoring congruity of the knee joint. For selective patients with malunions around the tibia plateau, this method might be an attractive option, with the potential to facilitate the most accurate correction possible. High accuracy was demonstrated in 2 of 3 cases. However, benefits must be confirmed in a prospective clinical study with a larger number of cases and outcome evaluation.

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