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Original Research

Three-Dimensional Correction of Complex Ankle Deformities With Computer-Assisted Planning and Patient-Specific Surgical Guides

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A R T I C L E I N F O

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A B S T R A C T

Three-dimensional computer-assisted preoperative planning, combined with patient-specific surgical guides, has become an effective technique for treating complex extra- and intraarticular bone malunions by corrective osteotomy. The feasibility and accuracy of such a technique has not yet been evaluated for ankle deformities. Four surgical cases of varying complexity and location were selected for evaluation. Three-dimensional bone models of the affected and contralateral healthy lower limb were generated from computed tomography scans. The preoperative planning software permitted quantification of the deformity in 3 dimensions and subsequent simulation of reduction, yielding a precise surgical plan. Patient-specific surgical guides were designed, manufactured, and finally applied during surgery to reproduce the preoperative plan. Evaluation of the postoperative computed tomography scans indicated adequate reduction accuracy with residual translational and rotational errors of <3 mm and $<6°$, respectively. Two patients required revision surgery owing to anterior osseous impingement or delayed union of the osteotomy. All patients were satisfied with the postoperative course and were pain free at a mean follow-up period of 2.5 (range 1 to 4) years. These promising results require confirmation in a clinical study with a larger sample size.

Complex bone deformities of the lower limb, resulting from either trauma or previously failed surgery, represent difficult problems for orthopedic surgeons (1). These malunions can alter the physiologic kinematics and thus increase the risk of persistent pain, loss of function, and development of osteoarthritis (2,3). If left untreated, advanced osteoarthritic changes of the ankle might only be salvaged by fusion or total ankle replacement. These salvage procedures are associated with accelerated degenerative changes of the adjacent joints (4) and revision surgery (5), respectively.

Supramalleolar corrective osteotomy is already an established technique for correcting the mechanical axis and kinematics of the ankle and thereby preventing further degeneration. To achieve adequate correction of the deformity, the preoperative planning should be as accurate as possible. Furthermore, the planning should not only include a thorough assessment of the deformity, but also the identification of any accompanying problems, such as soft tissue or vascular damage from previous trauma or surgery, which might be aggravated by another surgical approach. Conventional radiographs and computed tomography (CT) are important diagnostic tools but can still fail to provide 3-dimensional (3D) quantification of multiplanar complex deformities (6). Even if an optimal 3D surgical plan can be realized, precise intraoperative reproduction remains challenging and can lead to lower accuracy of the correction (7).

Several studies have reported that complex extra- and intraarticular malunions of the upper limb (7–10) can be accurately corrected with a combination of 3D computer-assisted planning and patient-specific surgical guides. To date, this technique has not been applied to complex malunions of the ankle. The aim of the present study was to present the preliminary results of this technique used in a case series with various complex deformities of the ankle.

Case Series

From September 2012 to September 2015, 4 consecutive patients, who had undergone corrective osteotomy of the distal tibia and/or fibula for either posttraumatic or inherited deformities of the ankle, were retrospectively included in the present study. Of the 4 patients, 1 was male and 3 were female, with a mean age of 42 (range 24 to 55) years. We performed regular follow-up examinations in our outpatient clinic at 8 weeks, 3 months, and 1 year after surgery. Pain at rest

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Table
Quantitative accuracy evaluation

Pt. No.	Site	Preoperative Error		Postoperative Error	
		Translational (mm)	Rotational (°)	Translational (mm)	Rotational (°)
1	Fibula	0.6, 0.2, −1.2	−0.7, 26.1, 5.5	0.4, 0.7, −1.0	−0.9, −4.6, 1.5
	Tibia	0.1, 0.8, −1.8	0.0, 0.0, 0.0	−0.6, −0.1, 0.0	−0.2, −0.4, −0.3
2	Tibia	0.8, 4.7, 3.6	−16.6, −3.9, −8.2	1.3, 1.3, 0.7	−1.1, −5.8, −3.3
3	Tibia	6.5, −13.1, −8.9	−6.7, −14.0, 12.5	−2.1, −2.9, −2.4	0.3, −2.6, 2.8
4	Tibia	−0.4, 0.0, 0.0	−9.8, −1.5, −2.4	−0.9, 0.9, 0.9	−0.8, 1.2, 1.8

The preoperative deformity presented as the computed positional error of the pathologic bone compared with the contralateral healthy side; the postoperative error corresponds to the residual deformity after corrective osteotomy. Pre- and postoperative errors both displayed in all 6 degrees of freedom (i.e., 3 translational [proximal/distal, dorsal/ventral, medial/lateral] and 3 rotational [varus/valgus, external/internal rotation, extension/flexion] error components). The low residual errors represent accurate reduction of the deformities in all 4 patients.

and during weightbearing was documented. Range of motion (ROM) of the ankle joint was measured using a goniometer.

Weightbearing was prohibited until the first clinical and radiologic follow-up examination. CT scans were obtained to assess both osseous consolidation of the osteotomy site and accuracy of the reduction. The rotational and translational error, calculated between the 3D preoperatively planned and postoperatively achieved reduction, corresponded to the residual deformity (Table). Regular radiologic follow-up examinations with conventional radiographs were performed. The included patients were followed up for ≥1 year. The patients gave written permission to report on their medical history and postoperative results. The responsible local ethics committee approved the study.

Preoperative CT scans (120 kV; Philips Brilliance 40 CT; Philips Healthcare, Best, The Netherlands) of the deformed and contralateral healthy lower limbs contained the entire tibia, fibula, and foot. From these data, 3D triangular surface models of the bone anatomy were extracted semiautomatically, using the segmentation functionality of Mimics software (Materialise, Leuven, Belgium). The cortical bone layer was identified with intensity thresholding, and the bone of interest was separated from the surrounding bone anatomy using a region growing algorithm. 3D preoperative planning was performed on a standard personal computer, using the custom-made software application, computer-assisted surgery planning application (CASPA; University Hospital Balgrist, Zurich, Switzerland). In the first step, the contralateral healthy lower limb was mirrored and used as a template, the so-called reference bone. The reference bone was aligned to the pathologic bone model using a surface registration algorithm (11). The proximal nondeformed region of the pathologic bone was automatically superimposed with the direct counterpart of the mirrored reference bone. Thus, the deformity of the distal part of the pathologic bone was determined in relation to the distal part of the reference bone and further specified in terms of rotational and translational deviation. The analysis was conducted using the calcaneus coordinate system according to the International Society of Biomechanics (12). In the next step, the pathologic fragment was virtually separated and reduced to its anatomically correct position by aligning it to the resembling part of the reference bone. In addition to the virtual osteotomy, the planning included the optimal choice of the surgical approach to the bone, localization and type of osteotomy (e.g., single-cut, wedge), and implant positioning and type.

The surgical guides were developed according to the individual anatomy of each patient. The guides were made of biocompatible polyamide (i.e., PA-2200). They were manufactured by Medacta International S.A. (Castel San Pietro, Switzerland) with a selective laser-sintering device. Sterilization was performed at our institution using conventional steam pressure. The undersurface of the guides was created such that the guide uniquely fitted the surface of the pathologic bone. Moreover, the guide covered the bone from different directions, ensuring a stable position. Cutting guides were used to direct the chisels or saws during osteotomy. The subsequent reduction was performed either with a separate reduction guide or with the final osteosynthesis plate over predrilled screw holes.

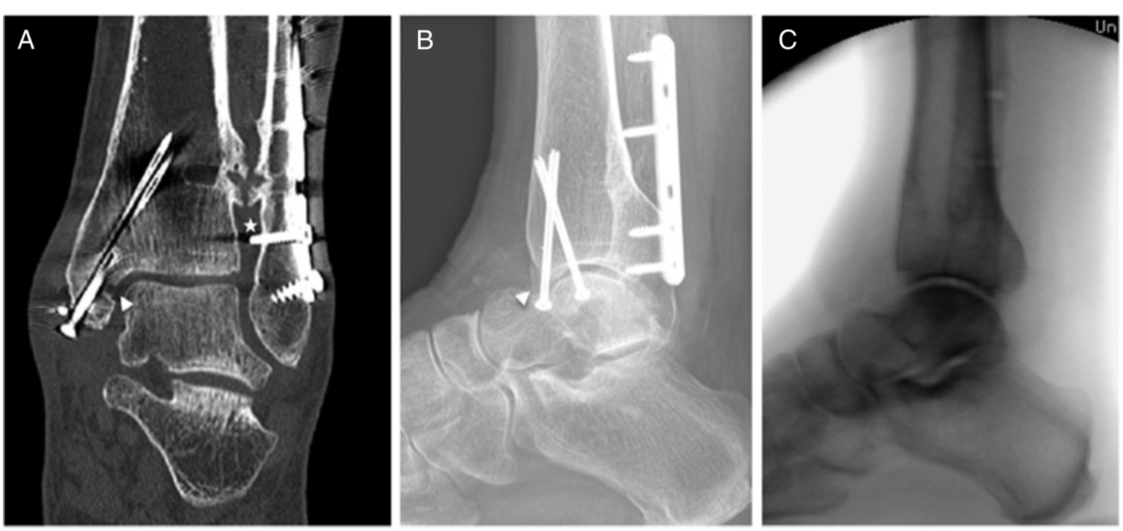

Fig. 1. Radiologic results for patient 1. (*A*) Malunited medial malleolus *(arrowhead)* and overlength of fibular screw *(star*; syndesmotic screw not depicted). (*B*) Anterior tibial osteophyte formation *(arrowhead)* 3 years postoperatively. (*C*) After arthroscopic debridement and implant removal.