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Three-dimensional corrective osteotomies of complex malunited humeral fractures using patient-specific guides

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Background: Corrective osteotomies of malunited fractures of the proximal and distal humerus are among the most demanding orthopedic procedures. Whereas the restoration of the normal humeral anatomy is the ultimate goal, the quantification of the deformity as well as the transfer of the preoperative plan is challenging. The purpose of this study was to provide a guideline for 3-dimensional (3D) corrective osteotomies of malunited intra-articular fractures of the humerus and a detailed overview of existing and novel instruments to enlarge the toolkit for 3D preoperative planning and intraoperative realization using patient-specific guides.

Methods: We describe the preoperative 3D deformity analysis, relevant considerations for the preoperative plan, design of the patient-specific guides, and surgical technique of corrective osteotomies of the humerus.

Results: The presented technique demonstrates the benefit of computer-assisted surgery for complex osteotomies of the humerus from a preoperative deformity analysis to the creation of feasible surgical procedures and the generation of patient-specific guides.

Conclusions: A 3D analysis of a post-traumatic deformity of the humerus, 3D preoperative planning, and use of patient-specific guides facilitate corrective osteotomies of complex malunited humeral fractures.

Level of evidence: Basic Science Study; Surgical Technique

Keywords: Three-dimensional; corrective osteotomy; patient-specific guides; humerus; capitulum; intra-articular; ramp; fan-shaped

Corrective osteotomies of malunited fractures of the proximal and distal humerus are among the most demanding orthopedic procedures.[6,8,11] Osteotomies are elective procedures scheduled in advance, providing sufficient time for a careful diagnosis and operative planning. Computer-based methods have become popular currently, especially in hand surgery,[19,20,24,28] because of the need for high performance and precision levels of complex osteotomies.[9] However, the quantification of the deformity, the development of feasible surgical procedures, and the transfer of the preoperative plan to the operating room are still major challenges, requiring sophisticated techniques and profound clinical expertise.

Ethics Committee approval was not necessary for this study (waiver no. 102-2015 issued by the Cantonal Ethics Committee Zurich, KEK Zürich).

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The benefit of computer-assisted planning and patient-specific instrumentation for corrective osteotomies of the upper extremity has already been emphasized.[15,18,19,21,25,26,28,30] With the increase in the experience of the computer-assisted techniques during the last decade, modifications of the technique for intra-articular deformities of the distal radius have been successfully developed.[20,23] However, the application of guides for corrective osteotomies of the humerus has been described only for the correction of distal extra-articular (varus and valgus) deformities. To the best of our knowledge, the application of 3-dimensional (3D) planned corrective osteotomies with patient-specific instrumentation has not been addressed for either post-traumatic deformities of the proximal humerus or intra-articular deformities of the humerus.

The purpose of this study was to provide a guideline for performing, in a standardized fashion, corrective osteotomies of the humerus with 3D preoperative planning and patient-specific guides. First, we present a detailed overview of existing techniques for 3D preoperative planning and patient-specific guide design that are modified for the humeral anatomy. Second, to enlarge the toolkit and to facilitate a broad range of osteotomies of the humerus, we provide several novel instruments for 3D preoperative planning and patient-specific guide design.

Materials and methods

3D deformity analysis and preoperative planning

The restoration of the normal humeral anatomy is an ultimate goal in performing corrective osteotomies of the humerus. Thus, it is crucial to assess the deformity as accurately as possible. In a template-based approach, the bone fragments are reduced to a 3D reconstruction template.[9] The contralateral healthy humerus is commonly proposed as a reliable reconstruction template.[19,25,27,30] The most fundamental step of the deformity analysis is the generation of 3D triangular surface models of the pathologic and contralateral humerus. The models are extracted from computed tomography (CT) scans (slice thickness, 1 mm; 120 kV; Philips Brilliance 40 CT; Philips Healthcare, Eindhoven, The Netherlands) using thresholding, region growing, and the marching cubes algorithm.[16] Thereafter, the models are imported into in-house–developed planning software, CASPA (Balgrist CARD AG, Zürich, Switzerland). The surface registration method, iterative closest point,[1,5] is applied to superimpose the models.[13,19] The key idea of the iterative closest point (ICP) algorithm is to determine the transformation (ie, the relative amount of 3D translation and rotation) necessary for superimposing the pathologic humerus to the mirror model of the contralateral and healthy humerus, such that the distance between the model surfaces is minimized. However, using the entire contralateral humerus in the registration can introduce errors associated with intraindividual side-to-side differences, especially in the torsional alignment.[7,27] Instead, for proximal (or distal) reconstruction, it is probably more suitable to register only the proximal (or distal) humerus region (Figs. 1, *A*).[17]

After the registration of the pathologic humerus to the reconstruction template, the humeral shaft serves as the reference fragment (Fig. 1, *A*). Before a malunion of (multiple) fragments is quantified, the malunited parts must be identified and separated on the basis of the previous fracture lines by creating virtual osteotomy planes.[9,10] Then, the reduction to the normal anatomy is simulated by registering the mobilized fragments to the reconstruction template (Fig. 1, *B*). The relative 3D rotation and the 3D translation between each fragment and the reference fragment quantify the malalignment (Fig. 1, *C*).

In addition, it is important to incorporate clinically relevant considerations in the simulated reduction (eg, by adopting the alignment of the fragments manually). For instance, a small shortening compared with the contralateral side might be preferable when a gap between the fragments can be avoided. In other cases, a realignment of the articular surface might be indirectly possible with a less risky osteotomy. Thereafter, the ideal surgical implant and the position of fixation must be identified. Finally, patient-specific guides are designed to transfer the preoperative plan into the surgery. As

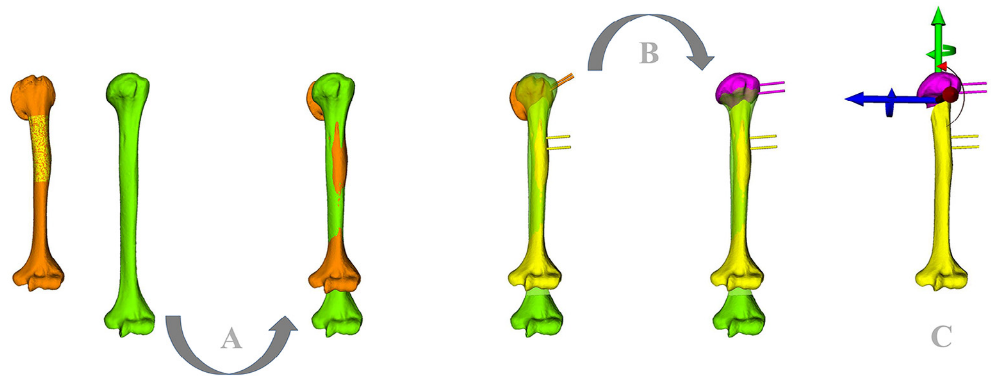

Figure 1 Deformity analysis and planned correction. A 3D model is illustrated of the pathologic humerus (*orange*), with the selected region (*yellow*) for the registration of the shaft (**A**) to the mirrored, contralateral humerus (*green*, target model). After the first registration (**A**), the shaft fragment serves as the reference fragment (*yellow*), and the proximal deformity is revealed. A second registration (**B**) of the humeral head fragment (*orange*) is performed to complete the reduction (*magenta*) to the target model. The relative transformation of the humeral head fragment quantifies the amount of the reduction and can be expressed in 6 degrees of freedom (ie, a rotation around a 3D axis and a translation along a 3D displacement vector) with respect to the humeral coordinate system (**C**). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)