Computer-aided osteotomy planning

Fuernstahl P¹, Schweizer A², Nagy L², Szekely G¹, Harders M¹

¹ Computer Vision Laboratory, ETH Zurich, Zürich, Switzerland
² Department of Orthopedic Surgery, Balgrist University Hospital, Zürich, Switzerland

fuernstahl@vision.ee.ethz.ch

Fractures of the forearm are among the most common orthopedic injuries. Marginally displaced fractures are usually treated by closed reduction or immobilization. However, depending on the degree of displacement, bone healing in non-anatomic position (malunion) may result, leading to pain, functional impairment, and aesthetic problems [1]. Particularly, deformities of the forearm bones can cause impingements and increased tension in ligaments, resulting in a limitation of the range of motion. A corrective osteotomy has become the standard treatment for malunited forearm bones to reconstruct normal anatomy.

In current clinical preoperative planning the contralateral healthy bone is used as a template. While angular deformities can be assessed using plain radiographs, rotational malunions require comparisons based on cross-sectional computed tomography (CT) images. However, state-of-the-art methods to quantify rotational deformities are error-prone since they rely on differences between a small number of anatomical landmarks, which are manually measured on 2-d CT slices. Therefore, the development of a computer-aided planning tool to accurately assess malunions and to plan osteotomies is of great clinical interest.
We present a comprehensive computer-aided planning system for corrective osteotomies. The key concept of our approach is to directly use the 3-d information of a patient's bone morphology, available from the CT data, in the comparison to the contralateral bone. The input data of the planning tool are 3-d models, generated from CT scans of the injured as well as the (mirrored) healthy bone. For segmentation of the image data an in-house method, based on bone enhancement filtering and graph cuts, is applied [2,3]. Triangular meshes are generated from the segmented scans using a Marching Cube algorithm. The overall process can be carried out in less than one minute with minimal user interaction.

In the first step of the planning process the exact location of the osteotomy has to be determined. To this end, a virtual cut plane is set that can be interactively placed and rotated in 3-d space. The plane defines the position on the bone where the malunion had occurred and divides the bone into a proximal and distal part, respectively. Our tool supports the user in finding the best osteotomy location by visualizing deformities between the injured and healthy bone. This is done by automatically registering the bones using the iterative closest point (ICP) method to measure deviations between the models. Non-uniform scaling is also incorporated into the registration process to compensate side-to-side variability of the bones, i.e. different bone lengths.
The virtual osteotomy is performed by separating the malunited bone mesh in a proximal and distal fragment according to the cut plane. Thereafter, either the proximal or distal part is matched to the opposed geometry. The Figure shows an example on the left-hand side where the proximal part of the malunited bone (red) was aligned to the contralateral anatomy (green). The transformation of this alignment was calculated by ICP registration of the proximal bone parts. The deformation of the malunited bone can now be represented by applying the same transformation to the distal bone fragment as shown in the Figure (left). In case of an uninjured bone both distal fragments would completely overlap. Therefore, the degree of malunion as well as the required correction can be exactly calculated by finding relative transformations that optimally match the malpositioned fragment to the contralateral bone. The transformations are calculated by minimizing the distance error between the two models. According to the type of osteotomy (e.g. constrained rotation or translation) the underlying mathematical optimization problem is solved in a least squares sense using a non-linear optimizer based on Sequential Quadratic Programming. The final result of the matching process is shown in the Figure on the right-hand side.

The required rotational and translation values for performing the osteotomy can be derived from the corresponding transformation matrices. However, the obtained measurements are described relative to a fixed coordinate system defined by the CT scanner that is not known during surgery. Therefore, the planning results have to be expressed in a local coordinate system that is fixed to the bone in order to intraoperatively identify the coordinate axes and origin. Several types of coordinate systems are provided in our system that are automatically initialized by identifying anatomical features. Additionally, the surgeon has the possibility to interactively define a custom coordinate system. The osteotomy planning is completed with a report describing the required correction of the malunited bone in the chosen coordinate system.

Using the developed system, our clinical partners carried out a pilot study incorporating osteotomy planning for three clinical cases. The results were compared with conventional planning by an experienced surgeon. While measured angular deformities only marginally differ from the conventional planning, the quantification of rotational deformities was significantly different in some cases. In case 1 the radius shaft was malunited with combined angular and rotational deformities. The difference between our approach and manual measurements was 6 degrees. In case 2, the radioulnar joint was angularly malunited. However, our system additionally calculated a rotational deformity of 18 degrees. Case 3 showed a malunited metacarpal
bone with a rotational difference of 10 degrees between computer-aided and conventional planning.

In conclusion, we have presented a computer-aided method for corrective forearm osteotomies, and have demonstrated that it is well suited to quantify complicated malunions with combined rotational and angular deformities. The proposed semi-automatic 3-d approach improves the accuracy of the planning compared to conventional 2-d methods that rely on manual measurements. The provided tools were developed in accordance with clinical practice and, therefore, allow an easy integration into existing planning processes.

References


