3D imaging in corrective osteotomy of the distal radius
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CHAPTER 9

COMPUTER-ASSISTED PLANNING AND NAVIGATION FOR CORRECTIVE DISTAL RADIUS OSTEOTOMY, BASED ON PRE- AND INTRAOPERATIVE IMAGING

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ABSTRACT

Malunion after a distal radius fracture is very common and if symptomatic, is treated with a so-called corrective osteotomy. In a traditional distal radius osteotomy, the radius is cut at the fracture site and a wedge is inserted in the osteotomy gap to correct the distal radius pose. The standard procedure uses two orthogonal radiographs to estimate the two inclination angles and the dimensions of the wedge to be inserted into the osteotomy gap. However, optimal correction in 3-D space requires restoring three angles and three displacements. This paper introduces a new technique that uses preoperative planning based on 3-D images. Intraoperative 3-D imaging is also used after inserting pins with marker tools in the proximal and distal part of the radius and before the osteotomy. Positioning tools are developed to correct the distal radius pose in six degrees of freedom by navigating the pins. The method is accurate (derr < 1.2 mm, qerr < 0.9°, mTRE=1.7 mm), highly reproducible (SED < 1.0 mm, SEq ≤ 1.4°, SEMTRE=0.7 mm) and it allows intraoperative evaluation of the end result. Small incisions for pin placement and for the osteotomy render the method minimally invasive.
INTRODUCTION

The annual occurrence of distal radius fractures is approximately 0.3% of the population (i.e., ~21 million individuals worldwide) [2],[17],[22],[24]. These cases are diagnosed with X-ray and mostly treated by aligning the bone segments followed by plaster application. The two bone ends malunite in a considerable number (5%) of these cases (~1 million/year Colles’ fractures worldwide) [8],[16], causing chronic pain, a reduced function of the hand, and as a consequence, (partial) disablement.

For patients that severely suffer from the malunion, a corrective osteotomy is performed in which the radius is cut at the fracture site and a bony wedge is inserted into the osteotomy gap to improve the pose of the distal end. Fluoroscopy is used to check for alignment before applying osteosynthesis. Preoperatively, the shape of the wedge is estimated from two orthogonal radiographs of the radius, and comprises its length and two inclination angles. However, 2-D images for planning and evaluation hide rotations about the longitudinal axis, possibly causing a misinterpretation of the corrective parameters. In fact, optimal pose correction of the articular surface in 3-D requires restoring six parameters: three displacements and three rotations.

In the last few decades a limited number of computer-assisted 3-D techniques have been proposed to improve the preoperative plan in which the unaffected contralateral radius serves as reference for restoring the affected side [2],[3],[1],[6],[9],[11],[19],[27]. The techniques mainly differ in the method for real-world repositioning of the bone segments. Unfortunately, all these studies, except the study of Croitoru et al. [9], used 2-D radiographs to evaluate the final pose. Moreover, in none of the cases was there prior information about the accuracy of the evaluation technique itself. It is therefore difficult to judge the true accuracy of these methods. Another important drawback of currently reported methods is their invasiveness: large incisions are required to approach the operation target.

A step towards a minimally invasive procedure is by utilizing a positioning tool, similar to a Taylor Spatial Frame (TSF)[21], that fixates the distal bone in the right position with respect to the proximal bone segment. These bulky TSFs are usually applied for correcting lower limb deformities and require manually adjusting six struts. Utilization of a standard TSF for corrective distal radius osteotomy requires long small-diameter pins, which would largely bend under tension of surrounding tissue during extraction of the bone segments. This renders a standard TSF less suitable for correcting the distal radius. In this paper we present a new method that introduces intraoperative 3-D imaging to navigate a distal radius segment to the correct position alignment. This technique allows accurate repositioning, immediate evaluation of the end result and the opportunity to adapt the treatment plan intraoperatively. For this new method, parallel pin pairs carrying marker tools are inserted in the proximal and distal part of the radius. The intraoperative scan introduces the marker tools into the preoperative plan and allows position calculations in 3-D space corresponding
to the correct alignment of the distal radius. A positioning tool is developed and applied to fixate the pin pairs and the distal radius segment in the right position after the osteotomy. This positioning tool is easily adjusted according to the results of image analysis by using a computer-controlled manipulator. Employing this method and treatment approach enables osteotomy between the pin pairs through small incisions, rendering the technique minimally invasive. This paper describes the new computer-assisted corrective distal radius osteotomy technique and evaluates the accuracy of the method as it is applied to a cadaver specimen.

MATERIALS AND METHODS

This section describes the computer-assisted corrective distal radius osteotomy technique, which includes procedures for: 1) preoperative virtual planning, 2) intraoperative navigation of the distal radius, and 3) evaluation of the end result. The procedure involves a number of registrations and calculations that are described in the appendix.

Preoperative planning

Preoperative planning is based on a CT scan of both the affected and the contralateral healthy radius. A dedicated application program was developed that guides the user through the image analysis steps as indicated by the block diagram of Fig. 1a.

a1) After loading the CT image, the affected radius is initially segmented by threshold-connected region growing [11], followed by a binary closing algorithm [7] for filling residual holes and closing of the outline. This intermediate result is used to initialize a Laplacian level-set segmentation growth algorithm [11] which advances pixel dispersion towards the edge of the bone.

a2) A polygonal description of the segmented bone is subsequently extracted at the zero level of the level-set image. This polygonal dataset is used for visualization and is also used to create a second polygonal dataset, by sampling the image intensity 1 mm towards the inside (high CT value) and outside (low CT value) of the bone, along the surface normal vector. The double-contour polygon is used during registration. The use of high and low intensity values close to the bone edge makes registration highly discriminative and provides effective data reduction, which speeds up the registration process [25].

In the next two steps, a3) and a4), the user clips a distal and proximal part of the radius polygon interactively. This excludes the fracture site which would not fit well when comparing to the contralateral radius of the opposite arm.
At a5) and a6) the resulting double-contour polygonal datasets of the distal and proximal radius segments contain sets of points at subpixel locations and with interpolated gray levels. These pointsets are registered with the reference image, which is a mirrored version (a7) of the healthy contralateral radius. This rigid pointset-to-image registration procedure [7],[11],[25] uses the Nelder-Mead downhill simplex optimizer with a six-parameter search space (three displacements, three rotations) while the correlation coefficient was used as metric unit, which quantifies how well the gray-level points fit the reference image.

Fig. 1. Block diagram showing the image analysis steps for the preoperative procedure and b) the intraoperative procedure. The transformation matrices and the double-contour polygons that result from the preoperative procedure are used for intraoperative navigation.
The results of the preoperative procedures are used for intraoperative navigation and for evaluation of the end result. These preoperative results include the transformation matrices for mapping the proximal and distal radius contours to the reference image, comprising three displacement and three rotation parameters each, and the double-contour polygonal datasets for registration. The coordinate system of the preoperative CT image containing the affected radius is used as reference coordinate system to express displacements and rotations throughout this paper.

Intraoperative procedure

During surgery, the distal bone segment needs to be aligned and fixated in the correct position with respect to the proximal bone segment. This is accomplished using a positioning tool (see Fig. 2). This positioning tool is very similar to existing external fixators, with the important difference that it is first adjusted to achieve fixation in the right configuration. Adjustment of the positioning tool is performed using an electromechanical manipulator (described below). The manipulator is controlled by software according to the results of pre- and intraoperative image analysis.

In a clinical setting, one fixation pin pair is first drilled into the proximal, a second into the distal bone segment using a guiding tool for parallel pin placement. Then, marker tools (described below) are slid over the pin pairs. These marker tools facilitate finding the pain pair position in 3-D space using an intraoperative CBCT scan (Pulsera with 3D-RX, Philips Healthcare, Best, The Netherlands) that is subsequently acquired. Next, the manipulator (in a sterile bag) is adjusted according to the findings of the intraoperative image analysis (described below). Brackets with patient-mimicking pin pairs are attached to the manipulator through the bag. Finally the orientation and positioning of the manipulator pin pairs is copied to the positioning tool. The positioning tool is finally fixated, unclamped from the manipulator, and clamped onto the patient pin pairs after osteotomy and extraction of the bone segments using a spreader. The positioning device can be removed after internal bone fixation.

The fixation pins, the parallel drilling tool, the marker tools, the positioning tool, and the manipulator brackets are all sterilizable.

Manipulator

A manipulator was developed (see Fig. 3) that serves to adjust the positioning tool. It contains three motorized translation stages (type 200CRI-R-M, Siskiyou, Grands Pass, OR) and three motorized rotary stages (type RSA 1.0i, Siskiyou, Grants Pass, OR). The translation stages are mounted orthogonally and carry the rotary stages, which are also connected orthogonally and rotate around an isocenter. The stages are connected to a six axes motion controller (type MC2000-6, Siskiyou, Grants Pass, OR), which allows quick and accurate adjustment of all six degrees of freedom in an automated fashion.
Two parallel pins are mounted at the isocenter of the manipulator which mimic the parallel pin pair on the distal radius. This pin pair can be translated and rotated in 3-D space with respect to a second, but fixed, parallel pin pair. The latter pin pair mimics the pins in the proximal part of the radius. The correction parameters that result from intraoperative imaging are sent to the motion controller to bring the movable pin pair into the right alignment. The positioning device, with unsecured hinges, is clamped onto the manipulator pins to copy the relative pin-pair position, and is subsequently fixed to the adjusted state by tightening the hinges. Finally the positioning device is unclamped, with the hinges still secured, from the manipulator pins and is clamped onto the actual radius pins to align the bone segments.
The physical range of manipulator rotations is -30 to 30 degrees. This is sufficient because the surgeon already observes an insertion angle during pin placement such that the angles remain small when the bones are properly aligned. The required manipulator rotations are therefore limited to residual rotations. The displacement range is 25 to 75 mm in the direction of the bone axis, with a possible manual offset up to 50 mm, in 5 mm steps. The displacement range in the other directions is -25 to 25 mm.

**Pin positioning with marker tools**

The above-described method requires knowledge about the 3-D placement of the pin pairs in the radius. This information is obtained from the marker tools that slide over the proximal and distal pin pairs (Fig. 4a). Each marker tool contains three metal spheres (Ø 5 mm) in a plane normal to the pins. One of the pins in each pair serves as a reference pin and supports the marker tool (see Fig. 4b). This defines the position of the marker plane along the pin pair. The marker locations can be detected from the intraoperative 3-D scan. The distance between the markers is unique and allows automatic distinction between the proximal and distal marker tool and automatic extraction of the orthogonal axes that define a local coordinate system for each marker tool (Fig. 4b).

The proximal coordinate system, obtained from the proximal marker tool, serves as a fixed reference and corresponds with the fixed coordinate system of the manipulator. The distal coordinate system, obtained from the distal marker tool, serves as a center of rotation during manipulation of the pins by the manipulator. The clamps of the positioning tool are supported by the same pins as the marker tools. This way, their local coordinate systems coincide and correspond with those defined at the supporting brackets of the manipulator (see Fig. 3a, 4b).

The metal spheres in each marker tool can easily be discriminated from the background in a 3-D scan, by thresholding at a user-selected level with subsequent labeling of voxels that belong to the same marker. Normally, 10 objects are detected this way: four pins and six markers. The spheres discriminate from the pins by their volume. With a constant voxel count for six marker spheres, deviating objects can be omitted. The intensity-weighted center of gravity of each marker object is taken as its position in 3-D space.

**Finding navigation parameters**

The intraoperative 3-D scan is used to introduce the marker tools into the preoperative plan and to calculate the displacement and rotation parameters for adjusting the manipulator. The marker tools are automatically detected by the software (Fig. 1b, step b1), which provides their position and orientation in 3-D space. The same intraoperative scan is used as a destination image for registration (b2) of the whole radius contour, that was obtained preoperatively (see Fig. 1a), yielding the matrix that transforms points from the
Together with the preoperative transformation matrices the translation and rotation parameters are calculated (b3, described in the appendix) that bring the distal pin pair and the distal radius segment in the right position.

**Software**

Dedicated software for this application was developed at our institute using the C++ programming language (Visual Studio 2005, Microsoft, Redmond, WA), with Qt 4.3.3 for GUI programming [5] (Nokia, Oslo, Norway), the Visualization ToolKit [20] (VTK 5.0.4) for visualization in 3-D, and the Insight ToolKit [11] (ITK 3.6.0) for segmentation and registration (Kitware Inc., Clifton Park, NY). The software combines the separate procedures.
for preoperative planning, intraoperative navigation and for evaluating the end result. Intermediate results, e.g., the transformation parameters for mapping double-contour polygonal datasets to different destination images (see appendix), are stored to disk and are automatically applied when necessary. The user is guided through all procedural steps as shown in Fig. 1, which renders the method easily applicable. At the end of the intraoperative procedure, the correction parameters are sent to the manipulator. An evaluation scan can be read by the software for calculating the residual error between the achieved and the planned distal radius alignment, based on the registration of the double-contour polygons and the evaluation image.

**EXPERIMENTS**

All CT images were acquired with a Brilliance 64-channel CT scanner (Philips Healthcare, Best, The Netherlands) (isotropic voxel spacing of 0.45 mm) and included the whole radius. Intraoperative 3-D scans were made with a mobile C-arm based Cone-Beam CT (CBCT) [7] (Pulsera with 3D-RX, Philips Healthcare, Best, The Netherlands). The volume of interest after reconstruction with the mobile CBCT system was approx. 14×14×14 cm (256³ voxels, with an isotropic voxel spacing of 0.56 mm). This field of view is sufficiently large to contain a part of the radius for registration and the marker tools, which are positioned close to one another and close to the skin. In all images the distal radius was positioned towards the +z-axis while the x-axis represented the radio ulnar direction.

When illustrating the accuracy and reproducibility of the positioning parameters from a series of measurements in this section, the average parameter value is used to represent the accuracy while the standard error (SE) represents the reproducibility. The results of registration are expressed in terms of displacements and rotations (order: first about the y axis, then z and x) but is also given in terms of the target registration error (TRE) [10]. In this parameter the target refers to a surface point of a polygon contour and the TRE is the distance between the planned and achieved position of such surface point. The mean distance between corresponding surface points in a polygon was finally used (mTRE) [14] to express the accuracy of registration by a single parameter.

**Evaluation of the technique**

**Marker detection**

During the intraoperative procedure we determine the correction parameters based on the local coordinate systems, which are derived from the marker tools in a CBCT image. For determining the accuracy and reproducibility of marker detection, a cadaver specimen was prepared by drilling parallel pins in the proximal and distal part of the radius while the
marker tools were positioned onto these pin pairs. The arm was repeatedly scanned 11 times with the mobile CBCT scanner, without repositioning the arm. No osteotomy was performed for this experiment. The distance between the markers in both marker tools was used as reference for accuracy assessment.

Position detection of markers in CT images is not required in the procedure for correcting the distal radius pose, but is of interest since CT scans were used to detect the accuracy of manipulator displacements and rotations. The same experiments as described above were therefore performed in the CT scanner, this time without the cadaver specimen.

Fig. 5a shows the accuracy of detecting the distance between the markers in both marker tools. The whiskers indicate the reproducibility ($\pm 1 \times SE$). The limited CT deviation ($d_{err} < 0.15 \pm 0.02$ mm) and CBCT deviations ($d_{err} < 0.11 \pm 0.02$ mm) allow accurate detection of the marker tool positions.

**Manipulator adjustment**

The accuracy and reproducibility of manipulator translations (specified accuracy $< 10$ μm) and rotations (specified accuracy $< 0.01$°) were assessed from CT scans by placing the marker tools on the pin pairs of the manipulator and determining the relative distance and orientation of the distal marker tool with respect to the proximal marker tool. For this experiment, the static part of the manipulator was constructed of a non-metal material to avoid excessive scattering and possible masking of the marker spheres in CT images. For the same reason, a non-metal arm was connected to the movable part of the manipulator, which extended the rotations to a metal-free zone. This method allows measuring orientations and translations when measured independently. Five arbitrary displacements and orientations were assessed this way within the full range of each stage. Fig. 5b and 5c show that both the relative displacement and orientation are adjusted with high accuracy ($d_{err} < 0.03 \pm 0.15$ mm and $\phi_{err} < 0.1 \pm 0.2$°).

![Fig. 5. a) CT and CBCT accuracy of detecting the distance between markers in both marker tools (n=11). Each group of three dots represents (see Fig. 4): p2-p1, p3-p1, p3-p2. b) Accuracy of manipulator displacements (n=5) and c) orientation (n=5) as measured with the CT scanner. The whiskers indicate the standard error.](image-url)
CT-CT and CT-CBCT registration

After segmentation from the CT image, and clipping of the virtual distal radius, the proximal and distal double contours are registered with the contralateral radius, which is basically a CT-CT pointset-to-image registration. The reproducibility depends on manual initialization of the registration procedure and on the noise pattern of the images. We investigated the accuracy and reproducibility of this step in the planning procedure by CT scanning a cadaver arm 11 times, without pins and markers. The first scan served to extract the double contours, the others served as destination images for registration. The distance between the centers of rotation and the difference between the rotation parameters before and after matching provided the accuracy and the reproducibility of the data. Fig. 6a and 6b show the accuracy ($d_{err} \leq 0.36$ mm and $\phi_{err} < 0.12^\circ$) and high reproducibility ($SE_d < 0.13$ mm and $SE_{\phi} < 0.07^\circ$) of preoperative CT-CT registration of the distal and proximal double-contour polygons to the reference images. The $mTRE$ in this experiment was $0.3 \pm 0.1$ mm for the distal segment and $0.4 \pm 0.1$ mm for the proximal segment. The residual bias is near equal for the proximal and distal segment. This is beneficial for position correction and evaluation of the end result, since these rely on the relative position of the two segments, which is therefore even more accurate.

The reproducibility of CT-CBCT registration was tested since it was used during the intraoperative procedure. For this test we used the first CT scan of the previous experiment and registered the double contour of the whole radius with the available fraction of the radius in 11 subsequent CBCT images. The CBCT scans were made of the same cadaver specimen without intermediate repositioning. Fig. 6c and 6d show that the reproducibility was high ($SE_d < 0.30$ mm, $SE_{\phi} \leq 0.33^\circ$). The accuracy was also high, based on visual inspection, although it cannot be expressed quantitatively, since the relative position of the radius in the CT and CBCT scanners is not known.

Clamping

The reproducibility of adjusting and clamping the positioning tool was tested by completing the whole procedure once, including setting the manipulator. The positioning tool was subsequently adjusted and clamped to the radius 12 times. A CT scan was made in each of these cases and included the positioning tool. For this experiment an ABS (Acrylonitril butadieen styrene) radius was created using stereolithography printing (SST1200es 3-D printer, Dimension Inc., Eden Prairie, MN). Fig. 7 shows the residual error ($d_{err} < 1.2$ mm and $\phi_{err} < 2.1^\circ$) and reproducibility (whiskers) ($SE_d < 0.4$ mm and $\phi_{err} < 1.6^\circ$). The $mTRE$ in this experiment was $1.8 \pm 0.4$ mm in this experiment, which expresses the position error of the distal end with respect to the proximal segment; it therefore includes registration errors of preoperative planning, intraoperative registration of the bone, navigation and postoperative evaluation, which compares the achieved pose with the planned pose.
A set of six artificial radii of different individuals was finally used to evaluate the entire procedure. In this experiment an initial CT scan of each artificial bone served as its own reference. A malunion was simulated by cutting out an arbitrary wedge and gluing the proximal and distal segments together with cyanoacrylate. A CT scan was subsequently performed, which served as the ‘affected’ radius image. The correction procedure was identical as for the artificial bone experiment described above. Table 1a shows the required correction parameters according to the planning procedure, and the residual error after correction and evaluation of the end pose ($d_{err} < 1.2$ mm and $\varphi_{err} < 0.9^\circ$). The $mTRE$ was $1.7 \pm 0.6$ mm in this experiment and includes the same sources of error described in the previous experiment.

Fig. 6. Top row: accuracy and reproducibility of CT-CT point-to-image registration, showing a) displacement and b) orientation parameters, ($n=10$). The whiskers indicate the reproducibility, represented by the standard error. Bottom row: reproducibility of CT-CBCT point-to-image registration, showing c) displacement and d) orientation, ($n=11$), for registration of the CT double-contour polygon of the whole radius with the available part of the radius in CBCT destination images.
A fresh frozen female cadaver specimen was used after thawing for at least 24 hours at 4°C, to evaluate the entire method in the following way:

**Preoperative procedure**

A CT scan was first made of the cadaver specimen; the image served as a reference image for reconstruction after introducing a malunion. A bone wedge was subsequently removed from the radius. The proximal and distal segments were connected using a two-component polyurethane rigid structure foam (type H400-AT, Vosschemie GmbH, Uetersen, Germany). A second CT scan was made of the ‘affected’ radius. Virtual planning was performed using the above-mentioned 3-D scans which resulted in the double-contour polygons of the bone, and the transformation matrices for mapping the affected bone segments to the unaffected reference image. Processing times were low for segmentation (~8 min), clipping (~1 min) and registration of both bone segments (~5 min).

**Intraoperative procedure**

Parallel pins were drilled into the proximal and distal bone and the marker tools were positioned over the pin pairs (Fig. 4a). A CBCT scan was made and the procedure continued with marker detection (~1 min) and registration of the double-contour polygon of the whole radius, to the CBCT scan (~6 min). This yielded repositioning parameters that were sent to the manipulator. The positioning tool was adjusted with the manipulator and clamped on the pin pairs of the cadaver specimen (Fig. 2). The gap between the bone segments was filled with the same polyurethane foam. After hardening, the positioning device was removed.

**Fig. 7.** Accuracy of whole procedure applied to an artificial radius. The whiskers indicate the reproducibility (SE) of adjusting and clamping the positioning tool (n=12).
Evaluation

Fig. 8a shows a surface rendering of the affected cadaver radius. The proximal and distal segments that were clipped, for registration with the reference image, are superimposed in Fig. 8b. Figures 8c and 8d show the distal end in the planned and achieved state. The end pose was compared to the planned state to calculate the residual correction parameters, as shown in Table 1b ($d_{err} < 1.8$ mm, $\varphi_{err} < 4.2^\circ$, $mTRE = 2.2$ mm).

<table>
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<th>Exp</th>
<th>Required correction</th>
<th>Residual error</th>
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<td>Rotation (degrees)</td>
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<tr>
<td>6</td>
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<tr>
<td>Ave</td>
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Table 1. a) Results of correcting artificial radii, showing the required correction parameters according to ‘preoperative’ planning, and the residual error according to postoperative evaluation of the end poses. b) Same parameters for the evaluation experiment with a cadaver specimen.

DISCUSSION

This study introduced a new method for preoperative planning of corrective distal radius osteotomies. The method combines the preoperative plan with a single intraoperative image to accurately reposition the distal radius with respect to the proximal bone segment. A manipulator was used to adjust a positioning tool, which is clamped to the pin pairs of the radius, and brings the distal end in place.
In clinical use the radiation dose is also of importance. The effective dose of the preoperative CT scan of both arms is ~0.6 mSv, which is a minor risk radiation exposure as qualified by the International Commission on Radiological Protection [12]. The additional dose to the patient due to the intraoperative scan with the CBCT scanner is ~12 μSv and is qualified a trivial radiation exposure dose [12].

Accurate intraoperative navigation of the distal segment is achieved by introducing marker tools that are supported by a reference pin in each pin pair. It has been shown that the relative position detection of these markers is accurate with a very small deviation ($d_{err} < 0.11$ mm) using a mobile CBCT scanner. As a consequence, the orientation of the marker tools is also detected with a high accuracy ($\phi_{err} < 0.22^\circ$) for both CBCT and CT images.

The accuracy of manipulator adjustment was tested from CT images with the distal marker tool at given positions and orientations with respect to the proximal marker tool. The accuracy for displacement and orientation were $d_{err} < 0.03 \pm 0.15$ mm and $\phi_{err} < 0.1 \pm 0.2^\circ$ which enabled accurate adjustment of the positioning tool.

Preoperative planning and intraoperative navigation in this method are based on registration of double-contour polygons with either a CT or CBCT destination image. The accuracy of preoperative registration was high ($d_{err} < 0.36$ mm and $\phi_{err} < 0.12^\circ$) with a high reproducibility ($SE_d < 0.13$ mm and $SE_\phi < 0.07^\circ$). The accuracy of intraoperative registration was high, based on visual inspection, although it could not be confirmed quantitatively since...
the relative radius position in CT and CBCT was unknown. The reproducibility of intraoperative registration was also high ($SE_d < 0.30$ mm, $SE_\phi \leq 0.33^\circ$). These results confirm the feasibility of utilizing the method for accurate correction of distal radius osteotomies.

The residual error of adjusting and clamping the positioning tool ($d_{err} < 1.2$ mm and $\phi_{err} < 2.1^\circ$) is still small but was relatively large compared to all other error contributions. While securing the clamps with a wrench, a slight offset is likely to be introduced by elastic behavior of both the manipulator and positioning tool. This needs further attention in future developments, especially if the method is combined with internal plate fixation, which exerts external forces to the clamp and may increase positioning errors.

The accuracy of the entire procedure is high ($d_{err} < 1.2$ mm and $\phi_{err} < 0.9^\circ$) as demonstrated with a set of artificial bones (Table 1a). The reproducibility ($SE$) as found in Table 1a is in close correspondence with the reproducibility of clamping and adjusting the positioning tool (Fig. 7). Utilizing the method on a cadaver specimen was also accurate ($d_{err} < 1.8$ mm and $\phi_{err} < 4.2^\circ$) although the errors are slightly higher than in the experiment with artificial bones. This additional error is probably due to external forces exerted by surrounding soft tissue on the positioning tool and the pin pairs, causing them to bend a little and increases the error.

In a similar 3-D study, Croitoru et al. [9] have used a standard navigation system with cameras for intraoperative repositioning of the distal radius and for positioning a fixation plate. They evaluated their system in a similar fashion with artificial bones and report comparable accuracy parameters. However, the reproducibility (reflected by the standard error) was markedly better using our technique.

Our new method relies on sufficient bilateral symmetry to use the contralateral radius as a reference for restoring the affected radius; this was done in previous studies [2],[3],[1], [6],[9],[1],[19],[27], based on 2-D images. The accuracy that we achieved with this new 3-D method may exceed the accuracy that is achievable due to bilateral differences. This issue warrants further investigation in future studies.

The new technique is a step towards minimally invasive surgery, where small incisions have to be made for pin insertion and to perform the osteotomy. In such an approach internal fixation may be achieved by inserting a quickly hardening bone substitute into the osteotomy gap. The major advantages of the proposed method are the ease of applicability in the operating room and the improved accuracy of repositioning and evaluation using all six degrees of freedom.

APPENDIX – CALCULATION OF POSITIONING PARAMETERS

The pre- and intraoperative procedures result in a number of transformation matrices that are used to correct distal radius positioning and evaluation of the end result. Each of these 4x4 transformation matrices is the result of registration of a double-contour polygon with any of the involved preoperative, intraoperative and evaluation scans. They include the
required rotations given the objects’ center of rotation and the required translations to map the object to the destination image. In this study, the geographical center, of the points in a polygonal dataset, is used as a center of rotation. Fig. 9 refers to the involved transformations.

The problem of correcting the distal radius alignment with respect to the proximal bone segment is similar to correcting the position of the distal coordinate system with respect to the proximal coordinate system. To this end, the markers that define the distal coordinate system are first transformed to the preoperative image that contains the affected radius (reference image) using $M_{w_i}^{-1}$ (Fig. 9c). Then the markers are brought to the position in a 3-D space that corresponds to the corrected position of the distal radius with transformation matrix $M_{corr} = M_{p_c}^1 M_{d_c}$. Finally the markers are transformed back to the intraoperative destination image with transformation matrix: $M_{w_i}$. Combining these steps, yield a transformation matrix ($M_s$) that transforms the distal coordinate system from the affected to the planned state within the intraoperative image:

$$M_s = M_{w_i}^{-1} M_{p_c}^1 M_{d_c} M_{w_i}^{-1}.$$

Fig. 10 shows the planned state of the local coordinate systems within the intraoperative image. The distance between the origins of the proximal and distal coordinate systems is described by vector $\mathbf{r}$. The projection of this vector onto the axes of the proximal coordinate system, which represents the fixed coordinate system of the manipulator, is the manipulator displacement ($d$) that we are interested in:

$$d_x = \mathbf{r} \cdot  \mathbf{e}_x; \quad d_y = \mathbf{r} \cdot  \mathbf{e}_y; \quad d_z = \mathbf{r} \cdot  \mathbf{e}_z,$$

with $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$ the unity vectors along the x, y and z axes of the proximal coordinate system.

The orientation parameters are derived from the rotation matrix $M_r$ that transforms the proximal coordinate system ($x-y-z$) to the distal coordinate system ($x’-y’-z’$), having the same origin (0,0,0) [20]:

$$M_r = \begin{bmatrix}
\cos \theta_{xz} & \cos \theta_{yz} & \cos \theta_{xz} \\
\cos \theta_{yz} & \cos \theta_{zx} & \cos \theta_{yz} \\
\cos \theta_{zx} & \cos \theta_{xy} & \cos \theta_{zx}
\end{bmatrix}.$$

The unit $x’$ axis is assumed to make the angles ($\theta_{xx’}$, $\theta_{xy’}$, $\theta_{xz’}$) about the x-y-z axes, and so on. The parameters for rotating the distal radius segment to the correct position can be derived from the rotation matrix above, by factoring the matrix as a product of rotations about the coordinate axes of the manipulator. For this, the order of the rotations has to be taken into account, which is defined by the manipulator. In our implementation, the order was first around the z axis, then around the x axis and finally around the y axis, giving:

$$M_M = M(\varphi_x) M(\varphi_y) M(\varphi_z) =
\begin{bmatrix}
 c_s c_x + s_s s_y s_z & c_s s_x - c_s s_y & c_s s_z \\
c_s s_x & c_s c_x & -s_x \\
-c_s s_y + c_s s_x s_z & c_s c_x s_z + s_s s_z & c_s c_x
\end{bmatrix}.$$
Fig. 9. Transformation matrices for mapping the double-contour preoperative distal, proximal and whole radius polygons of the affected radius in a), with: b) the preoperative reference image containing the contralateral unaffected radius (mirrored), c) the intraoperative image of the affected radius containing pins and markers, d) the evaluation scan to assess the residual error. The six translation and rotation parameters can be deduced from these matrices.

Fig. 10. Manipulator displacements are calculated from the distance vector \( \vec{r} \) between the proximal and distal coordinate systems. The projection of this vector onto the axes of the proximal coordinate system yields the translation parameters for adjusting the manipulator.
With $c_a = \cos(\phi_a)$ and $s_a = \sin(\phi_a)$ and:

$$
\begin{bmatrix}
1 & 0 & 0 \\
0 & c_a & -s_a \\
0 & s_a & c_a
\end{bmatrix}
\begin{bmatrix}
\cos \phi_x & 0 & \sin \phi_x \\
0 & 1 & 0 \\
-\sin \phi_x & 0 & \cos \phi_x
\end{bmatrix}
\begin{bmatrix}
\cos \phi_y & -\sin \phi_y & 0 \\
\sin \phi_y & \cos \phi_y & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

Equating $M_i$ and $M_{id}$ yields 9 equations with 3 unknown variables, from which $\phi_x$, $\phi_y$, and $\phi_z$ are solved.
REFERENCES


