Positioning Evaluation of Corrective Osteotomy for the Malunited Radius: 3-D CT Versus 2-D Radiographs

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Abstract

The authors retrospectively investigated the postoperative position of the distal radius after a corrective osteotomy using 2-dimensional (2-D) and 3-dimensional (3-D) imaging techniques to determine whether malposition correlates with clinical outcome. Twenty-five patients who underwent a corrective osteotomy were available for follow-up. The residual positioning errors of the distal end were determined retrospectively using standard 2-D radiographs and 3-D computed tomography evaluations based on a scan of both forearms, with the contralateral healthy radius serving as reference. For 3-D analysis, use of an anatomical coordinate system for each reference bone allowed the authors to express the residual malalignment parameters in displacements ($D_x$, $D_y$, $D_z$) and rotations ($D\psi_x$, $D\psi_y$, $D\psi_z$) for aligning the affected bone in a standardized way with the corresponding reference bone. The authors investigated possible correlations between malalignment parameters and clinical outcome using patients’ questionnaires.

Two-dimensional radiographic evaluation showed a radial inclination of 24.9°±6.8°, a palmar tilt of 4.5°±8.6°, and an ulnar variance of 0.8±1.7 mm. With 3-D analysis, residual displacements were 2.6±3 ($\Delta x$), 2.4±3 ($\Delta y$), and −2.2±4 ($\Delta z$) mm. Residual rotations were −6.2°±10° ($\Delta\psi_x$), 0.3°±7° ($\Delta\psi_y$), and −5.1°±10° ($\Delta\psi_z$). The large standard deviation is indicative of persistent malalignment in individual cases. Statistically significant correlations were found between 3-D rotational deficits and clinical outcome but not between 2-D evaluation parameters. Considerable residual malalignments and statistically significant correlations between malalignment parameters and clinical outcome confirm the need for better positioning techniques.
One possible complication of a distal radius fracture is malunion, which may result in a weak, deformed, stiff, or painful wrist. In some cases, a corrective osteotomy is needed to improve function and reduce pain. In current corrective osteotomy surgery, conventional planning and evaluation parameters are usually based on 2 orthogonal radiographs: a lateral and a posteroanterior view of the wrist joint. These radiographs are used to determine the radial inclination, palmar tilt, and ulnar variance, which are used to assess the rotations and translations needed to correct the position of the distal radius segment. Corrections are based on either population mean values or corresponding parameters of the contralateral wrist. The latter has been indicated as a better reference for restoring the position of the distal radius.

The planning, treatment, and evaluation of a corrective osteotomy are not unambiguous because measurement of 2-dimensional (2-D) radiographic parameters is hampered by inter- and intraobserver variations. Moreover, the reliability of measurements from 2-D images is hampered by overprojection, and rotations around the longitudinal axis of the bone are hidden, possibly causing a misinterpretation of the correction parameters. The postoperative position after a corrective osteotomy of the malunited distal radius may seem adequate on conventional posteroanterior and lateral radiographs of the wrist, but, due to the limitations of 2-D imaging, the distal radius can still be malpositioned postoperatively.

Recently, several computer-assisted 3-dimensional (3-D) methods have been proposed to measure malalignment before corrective surgery. An advantage of 3-D techniques is the ability to assess 6 malalignment parameters: 3 displacements along and 3 rotations around 3 orthogonal axes as opposed to the shortening and the 2 angulations seen on 2-D radiographs. Recent reports have shown a high intrinsic accuracy of these 3-D methods. In the current study, the authors retrospectively investigated the postoperative position of the distal radius after a corrective osteotomy that was based on conventional 2-D planning and 2-D intraoperative evaluation. It is known from studies performed with 2-D radiographs that the severity of a distal radius malunion is associated with higher disability, although statistically significant correlations have not been found. The authors tested the null hypothesis of equal 3-D positions in left and right radii and investigated whether 3-D positioning parameters were correlated with clinical outcome.

**Materials and Methods**

In this retrospective study, all patients (N=45) who underwent a planned corrective osteotomy of the distal radius that was evaluated intraoperatively using plain radiographs between 2000 and 2010 were contacted for a postoperative evaluation. Of these 45 patients, 5 were unavailable for follow-up, 5 were excluded from this study because of a contralateral wrist fracture, 6 did not want to participate, and 4 had other musculoskeletal diseases next to the distal radius fracture. The remaining 25 participants (23 women and 2 men; average age, 59 years [range, 43-75 years]) had a mean follow-up of 39 months (range, 6-86 months). Corrections had been planned with the corresponding radiographic parameters of the contralateral wrist (radial inclination, palmar tilt, and ulnar variance). Patients were treated by 3 different surgeons.

For the current study, all participants underwent a computed tomography (CT) scan of both forearms (Brillance 64 CT scanner; Philips, Cleveland, Ohio) (voxel size 0.45×0.45×0.45 mm, 120 kV, 150 mAs, pitch 0.6). In addition, posteroanterior and lateral radiographs of both wrists were obtained. A single hand surgeon (S.D.S.) measured the radial inclination, palmar tilt, and ulnar variance using the 2-D radiographs. This was done to exclude interobserver variability. In the 3-D evaluation, performed by a single investigator (J.C.V.) experienced with the software, residual malalignment parameters were analyzed. The method of finding these 3-D malalignment parameters has been previously described by Dobbe et al. The accuracy of this 3-D procedure has been proven to be precise, with a mean translation precision of 0.36±0.13 mm and a mean rotation precision of 0.12°±0.07°.
In this method, the mirrored CT image containing the uninjured radius was segmented to create a virtual 3-D model. Subsequently, a distal part of the bone model and a larger proximal part are selected and aligned with the CT image of the contralateral corrected radius of the participant by intensity-based image registration. The malalignment is then shown as the degree in which the poses of the distal segments differ (Figure 1). This allows for calculation of the displacements (Δx, Δy, Δz) and rotations (Δφx, Δφy, Δφ z) for aligning the affected bone with the reference bone. The 3-D malalignment parameters were expressed in terms of an anatomic coordinate system that is aligned with the segmented model of each reference radius. This allows for comparing the positioning parameters. All image analysis steps described above were performed using custom software.

For investigation of the relationship between malalignment and clinical outcome, the following standard validated questionnaires were used: Disabilities of the Arm, Shoulder and Hand Questionnaire (DASH), Michigan Hand Outcomes Questionnaire (MHOQ), and Patient Rated Wrist and Hand Evaluation (PRWHE). Wrist and forearm function were evaluated by measuring flexion, extension, pronation, supination, and radial and ulnar deviation. The authors compared the residual errors observed in this study with naturally occurring bilateral differences in the radius found in healthy individuals. The range of bilateral differences in healthy individuals is considered an acceptable range for comparison with the results obtained in this study.

This study was approved by the Medical Ethical Committee at the authors’ hospital, and informed consent was obtained from each participant. The authors evaluated positioning using 2- and 3-D techniques. The SD was used to represent the variability in residual malalignment parameters. To assess the relationship between the 2- and 3-D malalignment parameters, the authors performed univariate correlation analyses. They did the same for assessing correlations between these malalignment parameters and clinical outcomes. To establish statistically significant differences, paired t tests were used. All statistical tests were 2-sided, and a P value less than .05 was considered to indicate statistical significance.

**RESULTS**

**Radiographic 2-D Evaluation**

The results of the radiographic measurements for all 25 participants at follow-up are shown in Table 1, which shows the radial inclination, palmar tilt, and ulnar variance for healthy and corrected radii. The high SDs in the radiographic parameters for corrected radii compared with the unaffected radii are indicative of the variation due to planning and surgical treatment. Differences between radiographic parameters for healthy and corrected radii were calculated for each individual, resulting in a mean deficit and SD for the whole group (Table 2).

**Evaluation of Malalignment in 3-D Space**

The null hypothesis of equal 3-D positions in the left and right radii can be rejected. Malalignment parameters obtained by 3-D evaluation show residual errors in all 6 malalignment parameters (Figure 2). For comparison, the authors also display the naturally occurring differences between radii due to bilateral asymmetry in healthy individuals (healthy subjects).
asymmetry from a previous 3-D study in healthy individuals (Table 2; Figure 2). Larger SDs were found for all parameters in the patient group compared with bilateral differences in healthy individuals. This confirms suboptimal reconstruction.

**Correlations Between 2-D and 3-D Evaluations**

Two radiographic evaluation parameters show statistically significant correlations with related 3-D evaluation parameters. The radial inclination deficit correlates with parameter $\Delta \phi_y$ ($r=0.87$; $P<.05$), and the palmar tilt deficit with parameter $\Delta \phi_x$ ($r=0.78$; $P<.05$). Although a high correlation was found, individual differences between 2-D and 3-D images could be large for individual participants (Figure 3). No statistically significant correlation was observed between the ulnar variance deficit and parameter $\Delta z$ ($r=0.17$; $P>.05$).

**Clinical Outcome Parameters**

Clinical outcome parameters are shown in Table 3. The DASH score was graded as excellent (0-24), good (25-49), moderate (50-74), or poor (75-100). According to this classification, 19 (76%) patients had an excellent outcome, 3 (12%) good, 2 (8%) moderate, and 1 (4%) poor. These classifications were also seen for the other questionnaires.

**Correlations Between Malalignment Parameters and Clinical Outcome Parameters**

Correlation coefficients between the 2-D or 3-D malalignment parameters and clinical patient outcomes are shown in Table 4. The DASH, MHOQ, and PRWHE scores, as well as the extension, pain, and function outcome parameters, showed statistically significant correlations with 1 or more of the 3-D rotational parameters ($\Delta \phi_x$, $\Delta \phi_y$, $\Delta \phi_z$). No statistically significant correlation was found between the clinical outcome parameters and the displacement parameters $\Delta x$, $\Delta y$, and $\Delta z$. No statistically significant correlations are found between the 3-D malalignment parameters and flexion, pronation, or supination. In addition, no statistically significant correlations were found between 2-D radiographic parameters and clinical outcome parameters.

**DISCUSSION**

In the current study, the authors compared the position of the distal radius after a corrective osteotomy that was preoperatively planned and intraoperatively evaluated using established 2-D radiographic assessment with accurate 3-D imaging techniques. In addition, the authors in-

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**Table 2**

<table>
<thead>
<tr>
<th>Malalignment Parameter</th>
<th>3-D Assessment, Mean±SD</th>
<th>2-D Assessment, Mean±SD</th>
<th>Radiographic Deficit in Patients Per Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$, mm</td>
<td>2.6±3.0</td>
<td>-0.8±1.2</td>
<td></td>
</tr>
<tr>
<td>$\Delta y$, mm</td>
<td>2.4±3.1</td>
<td>-0.0±0.6</td>
<td></td>
</tr>
<tr>
<td>$\Delta z$, mm</td>
<td>-2.2±4.6</td>
<td>2.6±2.0</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi_x$, palmar tilt, deg</td>
<td>-6.2±10.3</td>
<td>0.1±1.0</td>
<td>8.1±10.6*</td>
</tr>
<tr>
<td>$\Delta \phi_y$, radial inclination, deg</td>
<td>0.3±7.7</td>
<td>-0.6±1.4</td>
<td>-0.0±6.1</td>
</tr>
<tr>
<td>$\Delta \phi_z$, deg</td>
<td>-5.1±10.1</td>
<td>0.5±5.0</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: 2-D, 2-dimensional; 3-D, 3-dimensional; deg, degrees.

*Column represents all patients (N=25) and shows 3-D malalignment parameters of the corrected distal radius compared with the contralateral healthy wrist in each patient.

*Bilateral asymmetry parameters of the radius in a group of 20 healthy individuals from a previous 3-D study.

*Related 2-D radiographic evaluation parameters.

*Deficits between radiographic parameters for healthy and corrected radii calculated per individual.

*Statistically significant difference between the corrected and contralateral healthy radius ($P<.05$).
vestigated correlations between residual malalignment parameters and clinical outcome. Surgery by different surgeons, different follow-up periods, and the diversity of patient ages allowed investigating general mean and SD in positioning parameters.

Clinical outcomes and residual malalignments in this patient group, assessed by postoperative radiographic measurements, are similar to previous retrospective studies on corrective osteotomies of the malunited distal radius. On average, the radial inclination of the corrected radius compared well with the contralateral healthy side. This suggests an overall good result. However, a large SD was observed (≥6.1), which indicates the inaccuracy of positioning for individual cases. The palmar tilt showed a large residual deficit between the healthy and corrected wrist and a large SD (±10.6). The large SD in the radiographic parameters could be explained by the fact that they are difficult to assess due to overprojection (Figure 1) and the fact that it is sometimes difficult to bring the distal segment of the radius into flexion intraoperatively due to scar formation on the dorsal side of the wrist joint. In addition, the rotational deformities observed in this study have been shown to affect the accuracy of measuring the radial inclination and palmar tilt using plain radiographs. The large variations observed in parameter $\Delta \Phi_z$, which is not observable on radiographs, affect the radial inclination and palmar tilt from 2-D radiographs. When investigating rotational malalignments for individual cases, the 3-D malalignment parameters can be exceptionally large: up to 26°.

Statistically significant correlations were found between the radial inclination deficit assessed per individual and the parameter $\Delta \Phi_y$ and also between the palmar tilt deficit and parameter $\Delta \Phi_x$. It is logical to find these correlations when projecting the 3-D bone on the $xz$ and $yz$ planes in Figure 1A. It yields a representation of the posteroanterior and lateral view as in standard radiographs. Although it is logical to find a relatively

<table>
<thead>
<tr>
<th>Outcome</th>
<th>DASH</th>
<th>MHOQ</th>
<th>PRWHE</th>
<th>Extension</th>
<th>Flexion</th>
<th>Pain</th>
<th>Function</th>
<th>Pronation</th>
<th>Supination</th>
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</thead>
<tbody>
<tr>
<td>Radial inclination</td>
<td>0.28</td>
<td>-0.19</td>
<td>0.31</td>
<td>0.14</td>
<td>0.26</td>
<td>0.23</td>
<td>0.28</td>
<td>0.09</td>
<td>-0.17</td>
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<tr>
<td>Palmar tilt</td>
<td>-0.36</td>
<td>0.24</td>
<td>-0.36</td>
<td>-0.31</td>
<td>-0.02</td>
<td>-0.32</td>
<td>-0.35</td>
<td>-0.13</td>
<td>0.11</td>
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<tr>
<td>Ulnar variance</td>
<td>0.19</td>
<td>-0.09</td>
<td>0.09</td>
<td>-0.10</td>
<td>-0.25</td>
<td>0.03</td>
<td>0.10</td>
<td>-0.19</td>
<td>0.09</td>
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<td>$\Delta x$</td>
<td>-0.12</td>
<td>0.01</td>
<td>-0.08</td>
<td>0.14</td>
<td>-0.09</td>
<td>-0.05</td>
<td>-0.06</td>
<td>-0.21</td>
<td>0.13</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>0.23</td>
<td>-0.32</td>
<td>0.33</td>
<td>0.20</td>
<td>-0.10</td>
<td>0.35</td>
<td>0.33</td>
<td>0.04</td>
<td>-0.03</td>
</tr>
<tr>
<td>$\Delta z$</td>
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<td>0.01</td>
<td>0.04</td>
<td>0.14</td>
<td>0.03</td>
<td>0.12</td>
<td>0.03</td>
<td>0.30</td>
<td>-0.14</td>
</tr>
<tr>
<td>$\Delta \Phi_x$</td>
<td>-0.29</td>
<td>0.26</td>
<td>-0.43*</td>
<td>-0.40*</td>
<td>-0.09</td>
<td>-0.45*</td>
<td>-0.43*</td>
<td>0.07</td>
<td>0.11</td>
</tr>
<tr>
<td>$\Delta \Phi_y$</td>
<td>-0.40*</td>
<td>0.30</td>
<td>-0.39*</td>
<td>-0.11</td>
<td>-0.17</td>
<td>-0.32</td>
<td>-0.37</td>
<td>-0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>$\Delta \Phi_z$</td>
<td>-0.42*</td>
<td>0.44*</td>
<td>-0.39*</td>
<td>-0.42*</td>
<td>-0.23</td>
<td>-0.28</td>
<td>-0.38</td>
<td>-0.30</td>
<td>-0.16</td>
</tr>
</tbody>
</table>

Abbreviations: DASH, Disabilities of the Arm, Shoulder and Hand questionnaire; MHOQ, Michigan Hand Outcomes Questionnaire; PRWHE, Patient Rated Wrist and Hand Evaluation.

*Indicates a statistically significant correlation (P<.05) between a 2- or 3-dimensional malalignment parameter and clinical outcome parameter.
high correlation between abovementioned parameters, it is not high enough to indicate total similarity between 2- and 3-D parameters as shown in Figure 3. The fact that no statistically significant correlation was found between the ulnar variance deficit and parameter Δz can be explained by the fact that Δz represents the bilateral difference in total length of both radii, whereas the ulnar variance reflects the relative position of the radius to the ulna. These are not to be compared with each other.

In the current study, finding a correlation between malalignment parameters and clinical outcomes is hampered by the fact that surgery is accompanied by soft tissue trauma with possible issues such as neuropathy, tendon problems, triangular fibrocartilage complex, or intercarpal ligament tears, which also influence clinical outcome.1,2 Two patients had a follow-up of less than 1 year, which may slightly affect clinical results; however, because the authors mainly focused on positioning of the distal radius, this will not affect analysis. The retrospective nature of this study did not enable the authors to include the preoperative assessment of the severity of the preoperative deformities or the inter- and intraobserver variability. Of course, CT imaging has disadvantages, such as additional time, cost, and extra radiation. Another shortcoming of CT imaging is the presence of metal artifacts caused by a fixation plate, which was sometimes still in situ. In Figure 4, the authors demonstrate the alignment procedure of the contralateral healthy radius model with the CT image of the corrected radius by intensity-based image registration. The plate did not affect the ability to match the bone segments.

To the authors’ knowledge, this is the first study that shows that angular deformities coexist with rotational deformities in distal radius malunions. This confirms that 2-D radiographs are not accurate in planning a corrective osteotomy because rotational deformities affect the appearance of the distal radius in 2-D radiographs and render estimating the radial inclination and palmar tilt inadequate.50 In addition, this study demonstrates a statistically significant correlation between 3-D rotational parameters and clinical outcome. This endorses the need for restoring rotational deficits that are unseen on 2-D images and using 3-D planning and surgical techniques for better positioning in 3-D space.

REFERENCES

17. Rieger M, Gabl M, Gruber H, Jaschke WR, Mallouhi A. CT virtual reality in the preoper-


