3D imaging in corrective osteotomy of the distal radius
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CHAPTER 4

ACCURACY OF POSITIONING THE DISTAL RADIUS USING AN ANATOMICAL PLATE

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ABSTRACT

In the last decade, several anatomical plates have been introduced to improve the result of open reduction and internal fixation (ORIF) surgery of the distal radius. We investigate, with the help of 3D imaging techniques, the accuracy and reproducibility of distal radius positioning using anatomical plates.

In this study distal radius fractures and correction of these fractures are simulated on plastic bone models of radii. We simulated a defect by removing an arbitrary wedge shape from these artificial radii. Two different physicians performed a correction by placing two different anatomical plate types according to the instructions of the plate manufacturers. The residual positioning errors of the distal segment in relation to the unaffected radii was determined using 3D imaging techniques. We compared the residual errors observed in this study with naturally occurring bilateral differences in the radius for healthy individuals. In a considerable number of cases positioning is not in agreement with generally accepted differences based on bilateral asymmetry in healthy subjects.

This pilot study is an indication on the accuracy of anatomical plates. We can conclude that positioning with an anatomical plate may lead to considerable residual errors for individual cases. Volar distal radius plate shapes are different among plate manufacturers. One plate may therefore perform better than the other for an individual patient.
INTRODUCTION

Fixed-angled volar distal radius plates provide a stable fixation after radial fractures or corrective osteotomies of malunited fractures.\(^1\)\(^-\)\(^4\) The latest variation of this type of plate is the anatomical plate, which is pre-shaped to optimally fit the contour of the distal radius. The anatomical plate is designed to bring the distal radius to its original anatomical position. This is important since it has been shown that there is a correlation between the accuracy of the anatomical reconstruction of a wrist and its function.\(^5\)\(^-\)\(^7\)

In the last decade, several anatomical plates have been introduced to improve the results of open reduction and internal fixation (ORIF) surgery of the distal radius.\(^8\)\(^,\)\(^9\) The manufacturers of anatomical plates claim that no intraoperative adjustment in terms of bending of the plate should be necessary, as the shape of the plate is already adapted to the contour of the bone. The shape of the plate can be used as an intraoperative guide to determine the correct position of the dislocated distal radius segment.

However, the contour of the plate may not always optimally fit the profile of the distal volar radius. In a previous anatomical study a statistically significant difference was observed in the morphology of the distal radius in 55% of the study population.\(^10\)\(^,\)\(^11\) This implicates that for these cases the application of the plate may lead to suboptimal plate positioning and a false position of the distal radius segment after plate fixation. In addition, shape differences exist between anatomical plates among manufacturers. Another anatomical study demonstrated a considerable variation in ideal plate location among anatomical plates of different manufacturers.\(^12\) It is sometimes unclear where to place the anatomical plate. Erroneous plate positioning by the surgeon can cause complications such as tendon ruptures or loss of reduction.\(^13\)\(^,\)\(^14\)

Based on these previous studies we hypothesize that results in positioning the distal radius segment using an anatomical plate may vary because of 1) anatomical variations in morphology of radii 2) variations in contours of the anatomical plate between manufacturers and 3) because of subjective plate placement by the physician. Although these parameters have been studied separately in other studies, the relative importance of each factor remains unclear. Therefore we investigate in this explorative study the accuracy and reproducibility of distal radius positioning using two anatomical plate brands, placed by two physicians in multiple radii. Evaluation is done with the help of 3D imaging techniques, which have made a tremendous development in recent years.\(^15\)\(^-\)\(^21\) We will compare the residual errors observed in this study with naturally occurring bilateral differences in the radius found in healthy individuals.\(^22\)
MATERIALS AND METHODS

In this study we simulate distal radius fractures and correction of these fractures on plastic bone models of radii. To create artificial radii models with different morphology we used CT scans of five healthy individuals (3 women and 2 men; average age 23 years). CT images are acquired with a Brilliance 64 CT scanner (Philips, Cleveland, OH; voxel size 0.45 x 0.45 x 0.45 mm, 120 kV, 150 mAs, pitch 0.6). The subjects had no history of wrist injury or other musculoskeletal disorders. The medical ethical committee of our hospital approved this study and we obtained informed consent from each subject. From the CT scans we segmented the right radius of each subject and we printed acrylonitrile butadiene styrene (ABS) models of these five different radii by additive manufacturing using a 3D printer (SST1200es 3D printer, Dimension Inc., Eden Prairie, MN). The resolution of this printer is 254 μm. We printed these five different radii (models 1 - 5) to investigate the effect of radius morphology on positioning, the differences between plates and the inter-operator variability on plate positioning (Fig. 1A). To separately investigate the reproducibility of placement by a single physician (intra-operator variability) we made four additional copies of the first radius (models 1B - 1E).

We made high-resolution CT scans of these physical models that served as a reference in finding residual positioning errors after plate fixation. We simulated a defect by removing an arbitrary wedge shape from each of the nine artificial radii (Fig. 1B). Two different physicians performed a correction of these affected radii by placing the anatomical plates according to the instructions of the plate manufacturer. The distal part of the plate was placed at the best possible position against the watershed line. The proximal part of the plate was placed in line with the shaft of the radius. This plate was fixated with cyanoacrylate glue (Fig. 1C and 1D). The physicians performed this procedure with a Synthes Plate (2.4 mm LCP distal radius plate, 04.110.440, Solothurn, Switzerland) and an Acumed Plate (Acu-Loc standard distal radius VDR plate, PL-DR50R, Hillsboro, OR, USA). All radii were corrected in random order.

After plate fixation, CT scans were made of the corrected physical models with the plate in situ. This allowed calculating the residual positioning errors of the distal segment in relation to the unaffected artificial radii scanned earlier. The method of finding these residual positioning errors is previously described by Dobbe et al.23 Using this method, the CT image containing the unaffected physical radius model was segmented to create a virtual 3D model of that radius. Subsequently, a distal part of this virtual bone model and a larger proximal part are selected and aligned with the CT image of the corresponding corrected radius by intensity-based image registration. Having the proximal segments aligned, the residual positioning error is then shown as the degree in which the poses of the distal segments differ. This allowed us to calculate the residual displacements (Δx, Δy, Δz) and rotations (Δϕx, Δϕy, Δϕz, rotation sequence y, x, z) for aligning the corrected radius with
each corresponding reference radius. To allow comparison of positioning results between radii of different morphology, an anatomical coordinate system is aligned with the virtual radius of each individual reference radius in the same way (Fig. 2). Positioning parameters are expressed in terms of these anatomical coordinate systems. All image analysis steps described were performed with custom software.

We compared the residual errors observed in this study with naturally occurring bilateral differences in the radius found in healthy individuals (n=20). In 3D imaging techniques, which are often used in corrective surgeries, the contralateral radius is used as a reference for correcting the affected radius. A better reference is not yet available. Therefore we consider the range of bilateral differences in healthy individuals as an acceptable range for comparison with the results obtained in this study.

Statistical Methods
Statistical analysis was performed non-parametrically. Differences in positioning due to morphological variation between radii were assessed by using a Friedman test. To assess whether there were differences in positioning between physicians and between the Acumed and Synthes plate we used the paired Wilcoxon signed rank test. For all these tests we used the dataset of the models 1 - 5. The dataset of the models 1, 1B - 1E was used to demonstrate a possible intra-operator variability on the positioning of the radius. A p-value <0.05 was considered statistically significant.

Fig. 1 A. Five artificial 3D radii with different morphology. B. A defect is simulated by removing a wedge shape from the distal part of each radius. C and D. In this example the affected radius is corrected with an Acumed plate and fixated with cyanoacrylate glue.
RESULTS

During the experiments, we experienced a good fit of the anatomical plates on the surfaces of the radii.
Figures 3 and 4 reveal that residual displacements along the axes of the anatomical coordinate system (Δx, Δy, Δz) are in the order of 0-2 millimeters while rotations around the axes (Δφx, Δφy, Δφz) can be up to 14 degrees in individual cases (Δφz1 in Fig. 4). The reproducibility of positioning on the same bone morphology for 5 times by both physicians (Fig. 3) and the variability in positioning on the distal radius segment of 5 different individuals (Fig. 4) are in the same order of magnitude but slightly smaller for the case of a repetitive plate placement with the same bone geometry (Fig. 3).
According the effect of variety in morphology, we only observed a significant difference for positioning parameter Δy (p < 0.05) between the different physical models 1 - 5. Positioning using an Acumed plate was statistically significant different for parameter Δφy (p < 0.05) compared to positioning using a Synthes plate. There were no statistically significant differences in positioning parameters between the two physicians.
Fig. 3 Residual positioning errors for physician 1 and 2 for one single radius morphology, for both the Acumed plate and the Synthes plate. The whiskers indicate the entire range of values, including outliers. The box indicates the range between the 25th to the 75th percentile. The median is indicated by a horizontal line.

Fig. 4 Residual positioning errors for physician 1 and 2 for multiple morphologies, for both the Acumed plate and the Synthes plate. The whiskers indicate the entire range of values, including outliers. The box indicates the range between the 25th to the 75th percentile. The median is indicated by a horizontal line.
Table 1 shows the results of comparing residual positioning errors with naturally occurring bilateral differences in healthy individuals. These bilateral differences between the right and left radius are ($\Delta x$, $\Delta y$, $\Delta z$): $-0.81 \pm 1.22$ mm, $-0.01 \pm 0.64$ mm and $2.63 \pm 2.03$ mm; and ($\Delta \varphi_x$, $\Delta \varphi_y$, $\Delta \varphi_z$): $0.13 \pm 1.00$ degrees, $-0.60 \pm 1.35$ degrees and $0.53 \pm 5.00$ degrees.

Table 1 displays the 95% confidence interval (average ± two standard deviations) as generally accepted range, since the contralateral side is always the best reference available in corrective surgery. This enables judging which cases are suboptimal. In a considerable number of cases positioning is less accurate compared to what can be achieved when the contralateral bone is used as reference. See Table 1 and the numbers between the parentheses which indicate the cases which fall out of the accepted range.

<table>
<thead>
<tr>
<th>Positioning parameter</th>
<th>Bilateral difference healthy individuals</th>
<th>Acumed [range experiments]</th>
<th>Synthes [range experiments]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accepted range</td>
<td>(out of accepted range)</td>
<td>(out of accepted range)</td>
</tr>
<tr>
<td></td>
<td>[range mean ± 2 SD]</td>
<td>N=20</td>
<td>N=10</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>[-3.25, 1.63]</td>
<td>[-0.60, 3.41] (2)</td>
<td>[-0.65, 2.22] (5)</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>[-1.29, 1.27]</td>
<td>[-2.02, 1.91] (5)</td>
<td>[-1.20, 3.29] (1)</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>[-1.43, 6.69]</td>
<td>[-4.90, 3.56] (5)</td>
<td>[-5.94, 1.71] (6)</td>
</tr>
<tr>
<td>$\Delta \varphi_x$</td>
<td>[-1.87, 2.13]</td>
<td>[-6.72, 11.02] (7)</td>
<td>[-4.92, 11.05] (8)</td>
</tr>
<tr>
<td>$\Delta \varphi_y$</td>
<td>[-3.30, 2.10]</td>
<td>[-9.32, 7.33] (6)</td>
<td>[-2.11, 10.48] (5)</td>
</tr>
<tr>
<td>$\Delta \varphi_z$</td>
<td>[-9.47, 10.53]</td>
<td>[-5.12, 4.69] (0)</td>
<td>[-5.11, 4.49] (0)</td>
</tr>
</tbody>
</table>

Table 1. The ranges of bilateral asymmetry in the control group (n=20) represent generally accepted ranges for the experiments in this study. For the Acumed and Synthes plates the results for both physicians were considered for the physical models 1 - 5 (n=10).

DISCUSSION

In this study we investigated the accuracy and reproducibility of distal radius positioning using an anatomical plate. We hypothesized that positioning may be influenced by 1) the different morphology between radii, 2) different contours of anatomical plates and 3) subjective placement of the plate by the physician.

1) An anatomically shaped plate should facilitate adequate bone positioning for every patient. Since the plates are designed for the average patient, and differences between bone morphologies exist, positioning errors will occur for individual patients. This study showed a large variation in positioning, mainly due to subjective placement by the physician. This explains why we could not establish the apparently smaller effect in malpositioning due to morphological differences for all parameters. However, we found a small but statistically significant difference for parameter $\Delta y$ ($p < 0.05$) between different radii.
2) When comparing positioning parameters between Acumed and Synthes plates we clearly observe a difference ($p < 0.05$) for $\Delta \varphi_y$ (see physician 1, Fig. 3 and 4). This can be explained by the clearly visible shape differences between the Acumed and Synthes plates (Fig. 5). As seen in Fig. 5 angle $\alpha$ is likely to influence parameter $\Delta \varphi_y$, and angle $\beta$ probably will have an influence on parameter $\Delta \varphi_z$. Different plates apparently provide different ways of positioning. These differences in plate definition are likely due to differences in the underlying subpopulations used by the manufacturers. The large differences between subpopulations are indicative for even larger differences between individuals. An anatomical plate may therefore perform very well for one patient but would be inadequate to use for another patient.

3) The large variability in positioning by both physicians is indicative for subjectivity in plate placement. We were not able to establish a statistically significant difference in placement between different physicians. This is due to the high intra-operator spread. (Fig. 3) In a considerable number of cases the residual positioning parameters of our experiments fall out of the generally accepted range of bilateral differences in healthy subjects. When considering all 6 positioning parameters at the same time for each experiment, 100% of the experiments has 1 or 2 positioning parameters that fall out of the range in healthy subjects.

In addition to the low statistical power, another limitation of this study is that during the experiments, the physician had a clear view of the whole radius. During actual surgery, a physician will not have such a clear view and positioning errors may be even larger in a
clinical setting than reported in this study. Moreover, in the operating room, the physician can use the ulna as guide for positioning the distal radius along the bone axis. In performing the correction with the anatomical plate on the physical radius models, the physicians did not have this reference. Therefore, parameter $\Delta z$ has no clinical relevance in this study. We did not include abnormal morphologies in this study. Deformities of the bone surface, such as in the case of malunions, may not allow the anatomical plate to fit on the bone morphology. We anticipate that using an anatomical plate for corrective osteotomies of the malunited distal radius will introduce higher positioning errors than reported in this study.

CONCLUSION

This was an explorative study to get an indication of the accuracy of anatomical plate positioning and the factors influencing the final positioning result. Future studies should be performed with more statistical power to quantify more accurately the effects of bone morphology and plate shape on positioning of the distal radius segment. Nevertheless, we can conclude that positioning with an anatomical plate may lead to considerable residual errors for individual cases that fall out of the generally accepted ranges in healthy subjects, mainly due to plate placement uncertainties.
REFERENCES


