3D imaging in corrective osteotomy of the distal radius
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CHAPTER 7

CORRECTIVE DISTAL RADIUS OSTEOTOMY. INCLUDING BILATERAL DIFFERENCES IN 3D PLANNING

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After a fracture of the distal radius, the bone segments may heal in a suboptimal position. This condition may lead to a reduced hand function, pain and finally osteoarthritis, sometimes requiring corrective surgery. Recent studies report computer-assisted 3-D planning techniques in which the mirrored contralateral unaffected radius serves as reference for planning the position of the distal radius before corrective osteotomy surgery. Bilateral asymmetry however, may introduce length errors into this type of preoperative planning that can be compensated for by taking into account the concomitant ulnae asymmetry. This paper investigates a method for planning a correction osteotomy of the distal radius, while compensating for bilateral length differences using a linear regression model that describes the relationship between radii and ulnae asymmetry. The method is evaluated quantitatively using CT scans of 20 healthy individuals, and qualitatively using CT scans of patients suffering from a malunion of the distal radius. The improved planning method reduces absolute length deviations by a factor of two and markedly reduces positioning variation, from $2.9 \pm 2.1$ mm to $1.5 \pm 0.6$ mm. We expect the method to be of great value for future 3-D planning of a corrective distal radius osteotomy.
INTRODUCTION

If bone segments are not correctly aligned after a distal radius fracture, they may unite in a suboptimal position. Besides a reduced function of the hand, such a malunion may cause chronic pain and early osteoarthritis. A well established but challenging treatment option is a corrective distal radius osteotomy. In this procedure the bone is cut (osteotomy) at, or near, the original fracture location. After the osteotomy, the distal bone segment is repositioned to bring it into original alignment with respect to the proximal bone segment. Conventional surgical techniques [12] have used preoperative X-ray images for alignment planning [11] using three degrees of freedom (DOF) (one translation: radial shortening; two rotations: radial inclination, palmar tilt [10]), and fluoroscopy images for intraoperative guidance and evaluation of the end position.

Recent papers describe techniques for planning a corrective osteotomy based on 3-D images [1][2][3][4][13][16]. This enables alignment of the bone segments in six DOF. During the 3-D planning phase, the image containing the contralateral unaffected radius is mirrored and is used as reference for estimating the original position of the distal segment [1] [2][3][4][13][16].

Several investigations report about the high symmetry between left and right radii [6][8][14]. These studies are based on 2-D imaging techniques. A recent 3-D study by Vroemen and coworkers [15], confirms the high bilateral symmetry although a relatively large rotational variation about the bone axis (0.53 ± 5.00° mm), and a relatively high length difference were observed (2.63 ± 2.03 mm) between left and right radii. Cadaver studies have shown that a rotational offset hardly affects the range of motion [5]. To the best of our knowledge there is yet no known relation between possible clinical limitations and a rotational offset. Slight rotational deviations are therefore considered acceptable. Bilateral length differences of the radii, however, may result in a positive ulnar variance which is an important radiological parameter related to clinical outcome [9]. It is therefore important to compensate for a bilateral length difference when the contralateral side is used in preoperative 3-D planning of a corrective distal radius osteotomy.

In this paper we describe a method for planning a distal radius osteotomy using 3-D imaging techniques. The method includes a linear regression model reflecting the relationship between intraindividual length differences of radii and ulnae, which enables compensating for bilateral asymmetry [15]. The method is evaluated quantitatively using CT scans of healthy individuals and qualitatively using CT scans of patients suffering from a malunion of the distal radius.
METHODS

This section describes standard 3-D planning of a correction osteotomy, compensation of bilateral length differences and the proposed method for including bilateral length differences in the planning of a correction osteotomy. In this paper we focus on correcting distal radius malunions although the method can equally be used for correcting ulna malunions.

General 3-D planning of a correction osteotomy
Starting point for our improved planning method is the computer-assisted 3-D planning of a correction osteotomy the way described by Dobbe et al. [4]. In this method -without length compensation- the affected radius is first segmented, resulting in a polygon model for visualization. Proximal and distal segments are clipped interactively and are subsequently matched with the mirrored image containing the contralateral unaffected radius, by intensity-based point-to-image registration. This yields a transformation matrix for aligning the proximal segment with the reference radius (MPR) and a transformation matrix for aligning the distal segment with the reference radius (MDR) (Fig. 1A). These matrices are combined into a correction matrix (MC = MPR-1 MDR) (Fig. 1A). These type of repositioning includes six degrees of freedom, being three translations along the three orthogonal axes defined by the scan, and three rotations about these axes.

Relationship between radii and ulnae lengths
It has been shown by Vroemen et al. [15] in a study with 20 right-hand dominant healthy volunteers that the dominant radii were 2.63 ± 2.03 mm longer compared to the contralateral side. Approximately the same results were found for the ulnae, which were also longer for the dominant arm (2.08 ± 2.33 mm). Moreover, a high correlation was found, in a linear regression model through the origin, between length differences of radii and ulnae (r = 0.88):

\[ \Delta Z_{\text{radius}} = C \Delta Z_{\text{ulna}} \]

With C being the proportionality constant. This relation is based on statistical analysis and enables compensating for bilateral length differences in cases of bone malunion under the condition that the three remaining lower arm bones are unaffected. Comparable relations were not found for the remaining translation parameters (radioulnar and dorsopalmar displacement) or for any of the rotation parameters (rotation about the bone axis, radial tilt, palmar tilt). It is therefore ill-founded to use any of the other parameters to further adapt positioning.
Planning with length compensation

Length differences due to bilateral asymmetry are compensated for during the planning procedure in the following way. At first the normal planning procedure is performed for the radius (section IIA) to find the correction matrix $M_C$ (Fig. 1A) that repositions the distal radius segment with respect to the proximal segment. Next, a similar planning procedure is repeated for the ulna to find the required length correction. In this procedure the ulna of the healthy arm is segmented and distal and proximal segments are clipped and registered with the mirrored image of the affected side, yielding a repositioning matrix for aligning the proximal segment with the ulna of the affected side ($M_{PU}$) and for aligning the distal segment with the ulna of the affected side ($M_{DU}$) (Fig. 1B). Combining these matrices in the same way as for the radius yields compensation matrix $M_A (= M_{PU}^{-1} M_{DU})$, and displacement vector $v$, which illustrates the displacement of the distal ulna due to bilateral differences. Since we are interested in compensating for length we project $v$ onto the gravitational axis of the ulna to find this length change, $\Delta Z_{ulna}$ (Fig. 1B). The gravitational axis is obtained by determining the three principle axes of rotation of the ulna using the moment of inertia tensor [7]. This tensor has three mutually orthogonal eigenvectors and three eigenvalues. The vector pointing in the direction of the long axis of the bone has the largest eigenvalue and is considered the gravitational axis. To finally compensate the radius length for bilateral differences, the distal radius is translated along the gravitational axis of the affected radius over a distance $\Delta Z_{radius}$ (using Eq. 1). Since the gravitational axis of the affected radius may be misoriented due to a deformity of the bone, the gravitational axis is determined for the healthy radius and then transformed (using $M_{PR}^{-1}$) to the affected radius.

Repositioning of the distal radius with respect to the ulna this way, is the 3-D equivalent to common 2-D practice in which the ulnar variance (normal range 0-2 mm [6]) of the contralateral side is taken into account.

Planning software

Custom planning software was written for segmentation, interactive clipping of bone segments and registration of these segments to the mirrored image containing the contralateral radius [4] resulting in the transformation matrices described in section C. The software was extended to calculate the gravitational axes of the contralateral radius and ulna in order to determine the displacement $\Delta Z_{ulna}$ along the bone axis and to calculate, using Eq. 1, the required compensation $\Delta Z_{radius}$ along the radial bone axis. The result of standard planning and length compensation are visualized for inspection.
Experiments

Accuracy and reproducibility of planning

To test the per-individual accuracy of our planning method with length compensation, we planned the position of the left distal radius using the same CT datasets of 20 healthy volunteers as used by Vroemen et al. [15]. In this evaluation experiment $\Delta Z_{\text{radius}}$ reflects the residual radial length deviation as compared to the original bone length, which serves as
ground truth. The datasets of the 20 healthy volunteers were acquired using regular-dose, high-resolution computed tomographic (CT) scans of both forearms using standardized methods (Philips Brilliance 64 CT scanner, Cleveland, OH; voxel size 0.45 × 0.45 × 0.45 mm, 120 kV, 150 mAs, pitch 0.6).

To avoid applying the proportionality constant \( C \) (Eq. 1) from [15] to the same group of individuals, we planned the position of the distal radius of one individual, while using the remaining 19 to determine the applicable proportionality constant \( C \). By repeating this procedure, 20 cases were evaluated independently to find the positioning accuracy.

When planning the position of a distal radius with length compensation, the left radius mimics an affected radius while the right arm serves as healthy reference. In actual patient cases, the user chooses clipping a distal and proximal segment such that the deformity is excluded. This guarantees an optimal registration of these segments with the unaffected contralateral side. For this reason the user freely chose a distal and a larger proximal segment for ‘patient cases’. To keep the experimental evaluation with healthy subjects unambiguous and irrespective of the clipped segment size we chose automatic clipping for these experiments: Ten percent of the distal radial and ulnar bone, and 90% of the proximal ulna were clipped for registration with the reference bone to find the positioning matrices. For the proximal radius, 70% was clipped hereby excluding the conically shaped distal region. Including this conical region would hamper registration in the likely case that the thicknesses of both radii are slightly different, resulting in a best fit that introduces a displacement along the longitudinal axis of the bone, toward the conical region. Next, we compared the planned position with the actual position of the left distal radius segment. In case of optimal planning the residual errors in all positioning parameters should be zero.

The whole procedure is repeated by planning the position of the right radius, to investigate whether left-to-right or right-to-left planning yielded the same results.

Evaluating the accuracy and reproducibility of the proposed length correction method depends on the accuracy of registration, especially in the z direction since the arm is positioned along this axis and we are considering length. Registration proofed to be accurate [4] with z translation errors better than (mean ± SD) 0.1 ± 0.1 mm.

**Patient evaluation**

The result of our planning method, which takes into account bilateral asymmetry, was evaluated for two patient cases eligible for corrective osteotomy. Since the original positions of these affected distal radii were not known a priori in these cases, the result of planning was evaluated qualitatively. In these patient cases positioning of the distal radius with respect to the ulna head was visualized for planning with and without length compensation.

The Medical Ethics Committee of the Academic Medical Center, University of Amsterdam, confirmed that for the above-mentioned retrospective patient evaluation, the Dutch Medi-
cal Research Involving Human Subjects Act (WMO) does not apply and further approval of the committee is not required.

RESULTS

Accuracy and reproducibility of planning

In our evaluation experiments with healthy volunteers, the dominant right radius was longer than the left radius in 19 of 20 cases (95%). In the remaining individual the right radius was slightly smaller (0.3 mm) than the left radius. When left was considered the affected arm (L to R correction), standard planning resulted in an absolute radius length change, $|\Delta Z| = 2.8 \pm 2.1$ mm, for the 20 healthy volunteers (Fig. 2, black squares; individuals are sorted by the magnitude of $\Delta Z$ “for standard planning”). If length compensation was included in the planning (Fig. 2, open squares) the absolute deviation improved in 75% of the cases to $|\Delta Z| = 1.5 \pm 0.7$ mm. In the remaining 25% of the cases, length compensation had an adverse effect although the residual absolute error was comparable, $|\Delta Z| = 1.6 \pm 0.5$ mm.

![Fig. 2. Residual radius length deviation ($\Delta Z$) when using the contralateral radius as reference (black squares and circles) and when length is compensated for bilateral differences using the ulnae (open squares and circles). L to R: Left radius is corrected using the right arm as reference; R to L: Right radius is corrected using the left arm as reference.](image-url)
If right was considered the affected arm (R to L correction), standard planning resulted in an absolute radius length change, $|\Delta Z| = 3.1 \pm 2.1$ mm (Fig. 2, black circles), for the same group of 20 individuals as referred to above. When length compensation was included (Fig. 2, open circles), the absolute deviation reduced in 14 of 20 cases (70%) to $|\Delta Z| = 1.6 \pm 0.6$ mm. In the remaining 30% of the cases, length compensation had the same adverse effect, but again with a comparable residual absolute error $|\Delta Z| = 1.8 \pm 0.5$ mm.

The above results are all very similar for correcting the radius length using either the left or right arm as reference. Small deviations occurred due to minor differences in geometry, which slightly affected registration, and due to small reproducibility errors in the registration procedure itself (see section 2.5.1).

**Patient evaluation**

Figure 3A shows the clinical case of a 64-year old female patient who suffered from malunion after a fracture of the right distal radius due to a high impact fall. The green distal part in Fig. 3A shows the distal segment used for planning and visualization. It was in a suboptimal position when length compensation was not applied during the planning procedure (Fig. 3B), causing the ulna to protrude into the distal ulnocarpal joint, which

Fig. 3. A) Patient case A showing a severe malunion of a collapsed distal radius. The green distal segment is used for planning and for visualization. B) Planned distal radius position, without length compensation showing an ulna plus which is likely to cause pain and damage due to ulnocarpal abutment. C) Normal radius-ulna relation restored by including length compensation.
very likely would cause pain and damage due to ulnar abutment. By including length compensation into the planning however, the distal radius was positioned in an improved anatomical relation with the ulna (Fig. 3C). The ulna position was fixed in the virtual representation of Fig. 3. This may falsely suggest fusion with the distal radius.

A second 25-year old female patient had suffered from a fracture of both the distal radius and ulna. During surgery, the ulna segments were fixated using a plate and screws. The radius fracture consolidated with the distal segment collapsed in the volar direction. An older fracture of the radius shaft consolidated in a dorsally dislocated position. This resulted in two malunions as shown in Fig. 4A. Not taking into account bilateral length differences in this specific case largely biased positioning of the distal radius (Fig. 4B, red segment). With length compensating using the two ulnae of this patient, distal radius positioning is restored to normal (Fig. 4C).

**DISCUSSION**

In this paper we investigated a method for planning a correction osteotomy of the distal radius, which uses the contralateral healthy radius as reference. In addition, we investigated applying a linear regression model describing bilateral differences between radii and ulnae in our planning to correct for length differences between left and right arms. This correction toward a better relation between radius and ulna is considered to be beneficial for patients since a positive ulna variance is negatively correlated to clinical outcome [9].

In many studies [1][2][3][4][13][16] the contralateral radius is used as reference in correcting a malunited radius. Since the original radius length is unknown and no better reference is available, this has been considered an acceptable reference. In this paper we showed that bilateral differences might cause considerable lengthening or shortening of the radius up to 7 mm for individual cases (Fig. 2) using this standard type of planning, compared to a maximum error of 2.6 mm when length compensation is taken into account. Including the ulnae lengths in preoperative planning has shown to reduce the overall absolute length deviation $|\Delta Z|$ from 2.9 ± 2.1 mm to 1.5 ± 0.6 mm.

In many 2-D studies the ulnar variance is used as an indicator of clinical result. A positive ulnar variance may lead to ulnocarpal abutment. To avoid damage to the articular surfaces of the distal radioulnar joint and the carpal bones, the ulnar variance should be restored as good as possible. The proposed method does not measure the ulnar variance but the residual length change does influence this parameter. Whether or not a change of ulnar variance, due to the residual lengthening or shortening of the radius, will result in poor clinical outcome remains undetermined. A positive ulnar variance exceeding 5 mm has been an indicator of unsatisfactory outcome in 40% of the cases [1]. In this respect our residual errors are relatively small. Small changes in ulnar variance may partially be compensated
for by the articular disk, with big disks (ulna minus) having a better tension transfer. Since a large variation of the ulnar variance exists in healthy individuals [10], this may especially be beneficial for those individuals who already have a large negative ulnar variance.

Utilization of the length compensation method to the patient cases as shown by Fig. 3 and 4 demonstrate its useful clinical applicability. In both these cases, the radius length would respectively be underestimated or overestimated if length compensation is left out of consideration (Fig. 3B and 4B). When length compensation is included however, the radius shows a visually acceptable position in relation to the adjacent ulna (Fig. 3C and 4C). Since the method compensates for length differences, it brings the distal radius to the same level as the distal ulna, which prevents ulnocarpal abutment. In that respect length compensation works equally well if the ulna is slightly shortened due to primary treatment, as may be the case in Fig. 4.

In conclusion, compensating for bilateral length differences using a linear regression model reduces the residual radial length deviation by a factor of two compared to conventional planning solely based on the contralateral radius. We expect the proposed method to be of value for future planning of corrective osteotomy surgery of the distal radius and ulna.

Fig. 4. A) Patient case B showing a malunion of the distal radius and a second deformity in the proximal direction due to a malunited shaft fracture. B) Distal radius position planned using the mirrored contralateral radius as reference. The distal radius is much too high in relation to the ulna. C) Same as b) but with length compensation.
REFERENCES


