3D imaging in corrective osteotomy of the distal radius

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CHAPTER 6

3D ASSESSMENT OF BILATERAL SYMMETRY OF THE RADIUS AND ULNA FOR PLANNING CORRECTIVE SURGERIES

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ABSTRACT

The contralateral unaffected side is often used as reference in planning a corrective osteotomy of a malunited distal radius. Two-dimensional radiographs have proven unreliable in assessing bilateral symmetry, so we assessed 3-dimensional configurations to assess bilateral symmetry.

We investigated bilateral symmetry using 3-dimensional imaging techniques. Twenty healthy volunteers without previous wrist injury underwent a volumetric computed tomography of both forearms. The left radius and ulna were segmented to create virtual 3-dimensional models of these bones. A distal part and a larger proximal part were selected from these bones and were matched with a mirrored computed tomographic image of the contralateral side. This allowed us to calculate the relative displacements \((\Delta x, \Delta y, \Delta z)\) and rotations \((\Delta \phi x, \Delta \phi y, \Delta \phi z)\) for aligning the left bone with the right bone segments.

We investigated the relation between longitudinal length differences in radiuses and ulnas. Relative differences of the radiuses were \((\Delta x, \Delta y, \Delta z)\): -0.81±1.22 mm, -0.01±0.64 mm and 2.63±2.03 mm and \((\Delta \phi x, \Delta \phi y, \Delta \phi z)\): 0.13±1.00°, -0.60±1.35° and 0.53±5.00°. The same parameters for the ulna were \((\Delta x, \Delta y, \Delta z)\): -0.22±0.82 mm, 0.52±0.99 mm, 2.08±2.33 mm and \((\Delta \phi x, \Delta \phi y, \Delta \phi z)\): -0.56±0.96°, -0.71±1.51° and -2.61±5.58°. There is a strong relation between absolute length differences \((\Delta z)\) between the radiuses and ulnas of individuals.

Substantial length and rotational differences around the longitudinal bone axis were observed in healthy individuals. Surgical planning using the unaffected side as a reference may not be as useful as previously assumed. However, including the length difference of the adjacent forearm bones can be useful to improve length correction in computer-assisted planning of radius or ulna osteotomies and in other reconstructive surgery procedures.

Bilateral symmetry is important in reconstructive surgery procedures where the contralateral unaffected side is often used as reference for planning and evaluation.
INTRODUCTION

Malunion is a complication after a distal radius fracture. (1) A malunion may cause pain, reduced motion, reduced grip strength, carpal instability, and eventually osteoarthritis. (2-4) Sometimes, a corrective osteotomy is performed to reduce the pain and improve function. The goal of the osseous correction is to restore normal relations in the distal radioulnar (DRU) joint.

In conventional surgery, measurements for planning the corrective osteotomy of a distal radius malunion are based on the correction of 3 radiographically obtained parameters: the radial inclination, palmar tilt and ulnar variance. (5-7) In early surgery, average values of population data of these parameters were used for surgical planning. (8) Subsequent studies concluded that the contralateral wrist serves as a better reference for planning and restoring the malunited distal radius. (9;10) Previous studies on bilateral symmetry of the bones are based on 2-dimensional (2D) radiographs. The reliability of measurements on 2D radiographs is frequently questioned in the literature (11-14) since these measurements are hampered by inter- and intra-observer variations and overprojection, which hides rotations around the longitudinal axis of the bone, possibly causing a misinterpretation of the correction parameters. Moreover, optimal planning of repositioning the articular surface requires restoring 6 parameters: 3 displacements and 3 rotations around 3 orthogonal axes. A corrective osteotomy should therefore be planned 3-dimensionally (3D) to allow correction of all 6 repositioning parameters, not only the shortening and the angulations seen on 2D radiographs.

In the last few decades a number of computer-assisted 3D techniques have been proposed for corrective surgery. (15-21) In these new techniques the unaffected contralateral radius serves as 3D reference for restoring the affected side. A recent report has shown a very high intrinsic accuracy of such a computer-assisted method. (22) A prerequisite for a proper 3D planning based on the contralateral radius is the presence of bilateral symmetry in all 6 parameters. Asymmetry may be a limiting factor in the accuracy of preoperative planning.

Until now, the assumption that there is indeed a bilateral symmetry of the forearm bones has not been studied in 3D.

In this paper, we investigated the bilateral symmetry of the radius and ulna in healthy individuals using 3D imaging techniques. Given the strong correlation between ulnar variance and functional outcome (23), it is important to restore the original length of the radius in order to obtain a proper relationship between the bones at the distal radioulnar joint. We know there is a natural length difference between the radiuses and ulnas of the left and right forearm in healthy individuals. (24) To compensate for this difference we investigated an approach for planning a corrective osteotomy by including the bilateral difference of the ipsilateral adjacent forearm bone, which is usually unaffected. In this
approach we assumed that the length of the radius is proportional to the length of the ipsilateral adjacent ulna.

There are numerous studies suggesting there is a bilateral symmetry of the bones in the forearm. (15-21) Bilateral symmetry is clinically relevant in the preoperative planning of corrective surgery where the contralateral healthy bone is used as a reference for correcting the affected bone. The clinical relevance lies also in providing a method for improved evaluation, which can be used in future studies to evaluate surgical results or compare the malposition of a malunited radius with standard difference parameters as observed in healthy individuals.

MATERIALS AND METHODS

We investigated the wrists of twenty right-handed healthy subjects (14 women/6 men, average age 28 years, range 22–56 years). The subjects had no history of wrist injury or other musculoskeletal disorders. This study was approved by the medical ethical committee of our hospital, and informed consent was obtained from each subject. All image analysis steps described in the following sections were performed with home-made software. (22)

Imaging and creation of a virtual 3D model

Regular dose, high resolution computed tomographic scans of both forearms are obtained using standardized methods (Philips Brilliance 64 CT scanner, Cleveland, Ohio, voxel size 0.45 × 0.45 × 0.45 mm, 120 kV, 150 mAs, pitch 0.6). The volunteers were scanned lying in prone position with their forearm in full pronation and extended above their head. In each subject the radiuses and ulnas were segmented by threshold-connected region growing, followed by a binary closing algorithm for filling residual holes and closing of the outline. (22) A 3D polygon was derived from the segmented data and served as a virtual 3D model of the bone. To allow comparison of the bilateral symmetry between subjects, an anatomical coordinate system was defined for every radius and ulna of each individual (25;26). (Fig. 1)

3D assessment of asymmetry parameters

A distal segment of 10% of the total bone length and a proximal segment of 80% of the total bone length were selected from the 3D virtual model of the left radius. These segments were matched with the mirrored CT image of the right radius by intensity-based image registration. (22) The registration procedure has proven to be accurate with translation errors of (mean ± SD) 0.36 ± 0.13 mm and rotation errors of 0.12 ± 0.07º. (22) The proximal segment of the segmented left radius was aligned with the proximal segment of the right radius. Asymmetry was then shown as the degree in which the positions of the
distal segments differ (Fig. 2). This same procedure was performed for the left and right ulnas.

Alignment by image registration resulted in transformation matrices, as described by Dobbe et al. (22) Asymmetry parameters were derived from these 4×4 matrices and expressed in terms of translation (Δx, Δy, Δz) and rotation (Δϕx, Δϕy, Δϕz) parameters.

This whole procedure was repeated vice versa by matching the right radius with a mirrored CT image of the left radius. This was done to investigate whether left-to-right and right-to-left matching led to similar asymmetry parameters.

Correcting for bilateral differences
When using the healthy contralateral radius in the preoperative planning of a corrective osteotomy for determining the lost height of the original radius position, there could be an over- or undercorrection an ulna plus or minus variation compared to the original situation. The calculated Δz of the distal radius segment may become deflected due to possible length differences between left and right forearm bones in 1 subject. (24)
To avoid such a possible over- or undercorrection in longitudinal direction (along the $z$-axis), the affected distal radius segment (Fig. 3a) was first aligned with the distal segment of the contralateral reference radius (Fig. 3c). Subsequently, the affected distal radius segment was moved in the longitudinal direction (along the $z$-axis) over an adjusted distance $\Delta z_{\text{RADIUS}}$ (Fig. 3b) to its unbiased position. When assuming proportionality between the lengths of ulna and radius, the adjustment for $\Delta z_{\text{RADIUS}}$ is given by:

$$\Delta z_{\text{RADIUS}} = \Delta z_{\text{ULNA}} \cdot C$$

where $\Delta z_{\text{ULNA}}$ is the bilateral length difference of the unaffected ulnas calculated by the procedure described before. $C$ is the proportionality constant. Once the value of parameter $C$ was obtained experimentally, it was used for unbiased estimation of the longitudinal position of the affected distal radius segment.
For continuous data, means and standard deviations (SD) were calculated. To assess the relationship describing the anatomical differences between radius and ulna, linear regression analyses was performed. This test was performed 2-sided and a P-value below 0.05 indicated statistical significance.

RESULTS

3D assessment of asymmetry parameters

For the radius and ulna, mean relative displacements and relative rotations (sequence y,x,z) of the distal segment among the twenty healthy subjects are displayed in Fig. 4. Left-to-right matching and right-to-left matching gave similar results, but in opposite direction, as expected. Average values are close to zero, except for $\Delta z$. Parameter $\Delta z$ was mostly positive in the left-to-right matching and mostly negative in the right-to-left matching, which indicated that the dominant right side was generally longer. In addition, parameter $\Delta \phi z$ also showed a larger spread for both the radius and the ulna.

Fig. 3. Additional corrective planning step for optimal longitudinal positioning of articular surfaces of the radius and ulna based on length difference between the ulnas.
Fig. 5 shows a scatter plot of length differences of the radiuses versus length differences of the ulnas with a regression line forced through the origin. Both right-to-left matching and left-to-right matching are included. There was a strong relation between absolute length differences ($\Delta z$) between the radiuses and ulnas of individuals (correlation coefficient 0.88; $P < 0.01$).

No relationship was found between rotational differences ($\Delta \phi z$) of radiuses and ulnas within individuals (correlation coefficient 0.23; $P = 0.34$).

Correcting for bilateral differences

The relationship between $\Delta z$ of the radius and $\Delta z$ of the ulna as depicted in Fig. 5 could now be used in the preoperative planning of a corrective osteotomy to correct for errors in the planned $z$-position that exist after matching with the contralateral bone. The proportionality constant follows after linear regression analysis and gives $C = 0.98$:

$$\Delta z_{\text{RADIUS}} = \Delta z_{\text{ULNA}} \times 0.98$$

This $\Delta z$ value can be used to correct the matching result for bilateral differences along the $z$-axis.

If the radius length is restored without correction for bilateral asymmetry, the residual positioning error is equal to the value as read from the vertical axis of Fig. 5. In this case the mean error ($\pm SD$) in the $z$-direction equals $2.85 \pm 2.07$ mm with the largest error being $7.30$ mm (lowest point in the scatterplot). With correction for bilateral symmetry, the adjusted $\Delta z_{\text{RADIUS}}$ is derived from $\Delta z_{\text{ULNA}}$ and the trendline in Fig. 5; the planning error is shown by the distance of each point to the trendline. In this case the mean error ($\pm SD$) in the $z$-direction
equals 1.44±0.78 mm with the largest error being 3.09 mm, which, on average, gives a smaller residual planning error.

**DISCUSSION**

Bilateral differences of the forearm bones were investigated and are important for planning for a 3D corrective osteotomy of the distal radius using the healthy contralateral side as reference. Differences were observed for $\Delta x$, $\Delta y$, $\Delta \phi x$ and $\Delta \phi y$, which are probably due to curvature of the shaft of the bone. This natural asymmetry in the forearm, at least in this small group of right-handed individuals, suggests that surgical planning using the unaffected side may not be as useful as previously assumed.

For $\Delta z$ and $\Delta \phi z$ even larger differences were observed. This limits the accuracy of the planning when using the contralateral side for reconstructive surgery. Especially the large differences in $\Delta z$ are relevant, since studies have shown that the ulnar variance is the most important radiological parameter affecting clinical outcome. (23) One of the most important reasons to perform a corrective osteotomy is reducing the resulting positive ulna variance, which may cause ulnocarpal abutment.

**Fig. 5.** Scatterplot showing length differences of the radiuses ($\Delta z_{\text{radius}}$) versus length differences for the ulnas ($\Delta z_{\text{ulna}}$), with a regression line. The squares indicate the results of left-to-right matching. The triangles indicate the results of matching right-to-left.
Restoring correct function of the hand requires correcting for the right length, for which the contralateral side is apparently not an optimal reference. Fortunately, a clear correlation was found between length differences ($\Delta z$) of radiuses and ulnas. The correct length can be estimated from the contralateral bone by compensating for the length difference in the same way as reflected by the ipsilateral bones (Fig. 3). The ulna length difference is a good reference for restoring the radius length difference and vice versa.

There was no clear relation between the $\Delta \phi z$ of the radius and the $\Delta \phi z$ of the ulna. The ulna can therefore not be used for compensating the sometimes large rotational difference around the longitudinal axis of the distal radius in planning a corrective osteotomy. The clinical relevance of $\Delta \phi z$ is yet unknown. In the study of Bindra et al. small bilateral differences were also found in longitudinal axis rotation between radiuses of an individual cadaver pair. They found that the mean bilateral difference of longitudinal axis rotation in radiuses with a malunited fracture was significantly higher statistically. (27) Other cadaveric studies concluded that an isolated rotational deformity has no functional relevance in the pronation and supination, although it shifts the range of motion (28;29). Further research is needed to investigate the relation between a residual rotation around the longitudinal axis ($\Delta \phi z$) and clinical outcome.

Rotation in the distal part of the radius around its axis is known to bias the assessment of the radial inclination and volar tilt parameters from 2D radiographs due to forearm rotation and due to overprojection. (11-13) This study showed a sometimes large bilateral difference in rotation of the distal segment along the bone axis ($\Delta \phi z$). This finding shows that correction based on the contralateral side may be markedly biased when using 2D radiographic parameters.

All subjects in this study were right handed, so only information about the relationship between right hand dominance and length of the bones can be provided. Our results are consistent with previous findings in the literature. (24) More research is needed to investigate the relationship in left handed individuals.

Two-dimensional planning based on radiographic assessment of angulation parameters is likely to bias the end result since the contralateral radius or ulna sometimes shows a large difference in rotation around the bone axis. Therefore 3D planning is essential. In addition, substantial bilateral asymmetry in radius and ulna length have been shown, which hampers using the contralateral side as reference in 3D planning of corrective surgery such as the osteotomy.
REFERENCES


