Complex Radius Shaft Malunion: Osteotomy with Computer-Assisted Planning

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Abstract We report about two cases with a combined axial and angular malunion of the radius shaft with functional loss of pro-supination. For the preoperative planning, a computer simulation was developed that allows the quantification of the malunion by comparing the 3-d surface model of the impaired bone with the contralateral anatomy. The proximal parts of the left and right radii are superimposed, while the different positions of the distal parts are used to quantify the malunion. This task is performed fully automatically which reduces the overall planning time. The osteotomies were performed according to the results of the computer-aided planning. The first case showed 1 year postoperatively an increase of pronation from 40° to 70° at expense of supination from 95° to 90°. The patient was practically pain-free and reported functional improvement. The second case showed 6 months postoperatively an improvement of supination from 15° to 40° and of pronation from 50° to 60°. The computer-assisted operation planning facilitated the quantification of combined axial and angular malunions which were difficult to detect on plain radiographs.

Keywords Radius malunion · Osteotomy · Computer planning

Introduction

Posttraumatic malunion of the radius shaft may lead to decrease of pronation, supination or an unstable and painful distal radioulnar joint [17, 24]. The mainstay of therapy is corrective osteotomy to restore normal anatomy [3, 14, 17, 24], thus improving the range of motion (ROM) and decreasing pain. Angular deformities are well visible on plain radiographs and allow an appropriate operative planning. Anatomical landmarks, radiographs from the uninvolved opposite side and intraoperative image intensifier are used as a guide for planning, intraoperative orientation and control of the result [14, 17, 19, 25]. However, the rotational component of a malunion is almost undetectable on plain radiographs [5–7, 23] and requires a more sophisticated side-to-side comparison of bony rotation profiles on computed tomography (CT) images [2, 6]. These methods assess rotational malunions based on few anatomical landmarks on 2-dimensional planes (2-d CT slices) in spite of the 3-d nature of the available data. Particularly, the orientation of the proximal radius part is difficult to define since it does not have prominent bony protrusions and is only assessed by the orientation of the bicipital tuberosity [2]. This may be one of the reasons why a high side-to-side variability up to 35° may occur which makes further planning more complicated [2, 17]. It is not known whether these high side-to-side variabilities also apply to the crank shaft shaped proximal part of the radius. Furthermore, conventional planning using plane X-ray techniques and CT-based rotational determination is very difficult in cases where combined multiplanar and rotational deformities occur. A correction of the rotational component would transfer an angular malalignment to another plane which makes planning as well as performing the reposition manoeuvre highly complex.

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We demonstrate preoperative computer-assisted planning on two cases with radius shaft malunions. All available volumetric data of the radius of both sides is used to quantify the malunion as robustly and accurately as possible. The first case had only minimal deformation in the rotational dimension, whereas the second case had gross multiplanar deformities, combined with a rotational malunion, illustrating the usefulness of our approach for a broad spectrum of clinical manifestations. Conventional planning was carried out along with the computer-assisted technique in order to demonstrate inaccuracies of the conventional method in case of combined deformities.

Computer-Assisted Planning

The first step for the computer-based approach is the acquisition of the data. The impaired and contralateral forearms of both patients were scanned using a Philips Brilliance 40 CT scanner with an in-plane resolution of 512×512 pixels (0.25×0.25 mm). The acquired slice-thickness was 2 mm in the first case and 1 mm in the second one, respectively. For the segmentation of the image data, an in-house developed method was applied [8, 10]. It should be noted that any other application able to extract bony anatomy would be suitable for this task.

3-d models were generated from the segmented scans using a Marching Cube [12] algorithm. The overall segmentation and model generation can be carried out in less than 1 min with minimal user interaction.

In the 3-d approach, the location of the osteotomy is defined by a virtual cut plane that can be interactively repositioned and rotated in 3-d space (Fig. 3). Thereafter, the malunion is assessed by aligning the proximal part of the bone with the contralateral anatomy. The alignment is automatically performed by using iterative closest point (ICP) registration [4]. After alignment, the degree of malunion as well as the required correction can be exactly calculated by finding a relative transformation that optimally matches the distal fragment to the contralateral bone. Basically, this transformation can be obtained by using registration techniques like ICP. However, the optimal transformation has to be constrained according to the type of the applied osteotomy. For instance, a Z-osteotomy requires a constrained translation along the bone length axis. Therefore, a non-linear optimization library is used to calculate the optimal constrained transformation by minimizing the distance between the distal fragments and the opposed bone [11]. Finally, the required rotation and translation values for performing the osteotomy can be derived from the corresponding transformation matrices.

The described parts of the computer-assisted method are freely available via several software libraries [1, 22]. Engineering effort was required to combine these algo-

rithms as described above. A more detailed description of the technical aspects can be found in [9].

First Case

A 24-year-old male student was referred to us with pain in his left non-dominant proximal forearm during and after sport (gymnastics), piano playing or working on the computer. He also complained about loss of strength in his forearm muscles and limited pronation. The patient mentioned a forearm shaft fracture at the age of 10 which was treated conservatively after closed reposition. Thereafter, he was pain-free for several years until he started performing gymnastics more intensively. The limited pronation was compensated by the shoulder, leading to symptoms in the upper arm. Different forms of physiotherapy did not improve his symptoms. At physical examination, there were symmetrical forearm muscles and no pressure pain detectable. ROM showed a decreased pronation compared to the opposite side (pronation–supination left side, 40° – 0° – 95° ; right side, 70° – 0° – 85°) with symmetrical ROM at wrist joint (extension–flexion, 75° – 0° – 60° ; ulnar–radial deviation, 40° – 0° – 10°), elbow joint (flexion–extension, 145° – 0° – 5°) and pinch grip (both sides 45 kp, JAMAR Dynamometer, Sammons Preston Inc, Bollingbrook, IL, USA).

Plain radiographs of both forearms showed almost symmetrical angular measures except for a loss of the left radial bow (valgus deformity) of approximately 3° (Fig. 1). It was assumed that an axial (rotational) malalignment was present, not visible on plain radiographs. A CT scan of both forearms was performed to determine radial torsion using the method described by Bindra et al. [2]. In Bindra's method, the torsion profile is defined as the angle between the tangent to the flattened cortical surface of the bicipital tuberosity and the transverse line bisecting the radial and ulnar borders delimiting the square-shaped cross-section of the distal radius proximal to the lunate fossa. The affected left side showed a torsion angle of 30° and the right side a torsion angle of 57° (Fig. 2), with a calculated rotational malunion of 27° . The fracture of the radius was at the transition zone between the two proximal quarters of the radius where a collision with the ulna is more likely even with small angular deviations.

Therefore, computer-assisted planning was carried out for a more detailed comparison of both radii. The position of the virtual osteotomy was defined 68 mm from the proximal radius head as demonstrated in Fig. 3. The malunion was assessed by aligning the proximal parts of the radii and calculating the best transformation to match the distal fragments. Figure 4 depicts the 6 months postoperative radiographs showing the united bone. Because of the mainly rotational correction, the angular

Figure 1 Preoperative planning on plain X-ray, anteroposterior view. An angular deformity (valgus) of 3° could be measured.

changes are almost not apparent. The computer-assisted approach allowed a more exact quantification, particularly of the rotational components. A rotational malalignment of 22.5° (4.5° difference to Bindra's method) and a valgus deformity of 3.5° were obtained.

Based on the planning data, the selected surgical approach was to derotate (pronation), to increase radial bow and to flex the presumptive distal fragment in relation to the proximal fragment of the radius (Fig. 3). From the two angular deformity components (flexion–extension, ulnar–radial deviation) the true plain deformity angle and its axial orientation was calculated beforehand according to the method described by Nagy et al. [17]. The surgery was performed in upper arm exsanguination. A Henry approach was used to expose the proximal third of the radius, the M. supinator was detached, whereas the M. pronator teres was left intact. After marking the radiocarpal and the radiohumeral joint, the exact height of the planned osteotomy was determined. A 3.5 mm 6-hole LC-DC plate (Synthes, Oberdorf, Switzerland) was contoured and fixated at the presumptive proximal fragment. The planned angular

corrections were incorporated in the contouring of the plate. The distance of the bone to the distal end of the plate (trigonometric calculation from the corrective angle) was used as an orientation according to the method described by Nagy et al. [17]. Additional K-wires were inserted into the presumed proximal and distal fragments to control rotation. After the osteotomy, the proximal fragment was first fixated to the plate. Thereafter, the correction of the rotation of the two fragments in the long axis was performed according to the preset K-wires. The deformities in the flexion and extension planes were then cleared by rotation of the fragment in the concerned axis. In this way, the distal fragment was approximated to the plate and screwed in place. The plate itself was fixated to the lateral side of the radius to prevent impingement between radius and ulna. The intraoperative ROM of pronation–supination was 70° – 0° – 80° . Postoperatively, the forearm was mobilised immediately under control of an occupational therapist. At the follow-up control 1 year postoperatively, the patient was almost pain-free. Physical examination depicted a ROM of pronation–supination of 70° – 0° – 90° , symmetrical elbow

Figure 2 Measurement of the rotational deformity according to method of Bindra where an increased supination of 27° (left side) was found. Single lines with square ends depict the distal radius and lines with circle ends the proximal radius (bicipital tuberosity).

Figure 3 3-d models of the malunited radius (*red*) and the proximally matched mirrored radius (*blue*) of the contralateral side are shown. The presumptive cutting plane (*grey*) determines the matching area distally.

flexion–extension of 145° – 0° – 5° , and grip strength of 42 kp on both sides. Plain radiographs showed a consolidated osteotomy with the initially intended correction of the radius. A CT scan of the corrected forearm was performed and compared with the mirrored radius previously scanned in order to control and quantify the surgical correction. The analysis using the computer tool showed that the rotational and angular deformities were reduced by 18° and 2° , respectively.

Second Case

A 51-year-old male mason complained about stiff and painful pronation–supination movement in his right dominant forearm. The patient had a fracture of the radius shaft 1 year ago due to direct trauma which was treated conservatively. Nevertheless, he continued to work as a mason. At physical examination, there was an unstable painful DRUJ detectable. ROM showed a decreased supination compared to the opposite side (pronation–supination right side, 50° – 0° – 15° ; left side, 50° – 0° – 90°) with ROM at wrist joint (extension–flexion, 60° – 0° – 70° ;

ulnar–radial deviation, 30° – 0° – 20°) and elbow joint (flexion–extension, 135° – 15° – 0°), and pinch grip of 41 kp on the right and 57 kp on the left side (JAMAR).

Plain radiographs of both forearms showed a complex malunion of the right radius shaft (Fig. 5) between the middle and proximal third with shortening and consecutive subluxation of the DRUJ. Additionally, a loss of the left radial bow (valgus deformity) of approximately 9° and an extension deformity of 2° compared to the contralateral side were conventionally measured. It was assumed that an axial (rotational) malalignment was present, difficult to measure on plain radiographs. A CT scan of both forearms was performed to determine radial torsion by the method described by Bindra et al. [2]. The affected right side showed torsion towards pronation of 65° .

The computer-assisted quantification (Fig. 6) of the malunion resulted in 65° pronation deformity, 15° valgus deformity, 1.8° extension deformity, and a lateral displacement of 10 mm (Fig. 6). Due to the distinct rotational deformity, the measurement of the angular deformities, obtained by conventional planning using plain X-rays, were very unreliable. This was verified by virtually performing two osteotomies according to the result of the computer-assisted and conventional planning, respectively (Fig. 7).

The planned surgical approach was to derotate (supination), to increase radial bow, to flex the presumptive distal fragment and to correct the lateral displacement. The surgery was performed in the same manner as described above. A 3.5-mm 8-hole LC-DC plate (Synthes, Oberdorf, Switzerland) was contoured and fixated at the presumptive distal fragment. The planned angular corrections, which were calculated before, were incorporated in the contouring of the plate. A Z-osteotomy was performed such that both brackets of the two fragments could be placed on top of each other in order to correct the shortening after derotation. Thereafter, the proximal fragment was fixated to the plate (lateral side of the radius). Intraoperative testing of the pronation–supination movement after derotation by 65° showed no further limitation of the supination, but the patient's pronation ROM was limited to 20° . Therefore, we

Figure 4 Six months postoperative radiographs showing the already healed osteotomy.

Figure 5 Preoperative plain X-rays of the right (operated, top) and left forearm showing deformity of 9° in valgus (loss of radial bow) and 2° in extension. These values were calculated by comparison with the contralateral X-rays of the forearm according to the centre lines of the corresponding shaft fragments.

decided to derotate only by 45° in order not to sacrifice too much of pronation. The definitive intraoperative ROM of pronation–supination was 40° – 0° – 50° . Total ROM increased from 65° to 90° . CT scans and 3-d reconstruction postoperatively showed a restored alignment of the radius and DRUJ (Fig. 6). No significant angular deformities compared to the contralateral bone were detected by the planning system. A rotational difference of 17° was measured which is in accordance with a surgical correction of 45° . Postoperatively, the forearm was mobilised immediately under control of an occupational therapist. At the follow-up control after 6 months, the patient was pain-free at rest, although he suffered from slight ache in his wrist during hard work as a mason. The osteotomy was consolidated (Fig. 8). Physical examination depicted a ROM of pronation–supination increased to 60° – 0° – 40° , elbow flexion–extension was 140° – 0° – 0° and grip strength was 39 kp for the right (operated) and 59 kp for the left side.

Figure 6 Proximally aligned 3-d models of the malunited radius (red), the mirrored radius of the contralateral side (blue) and the corrected radius postoperatively (green). The presumptive cutting plane (grey) determines the matching area distally.

Discussion

Multipplanar corrective osteotomies of the shaft of the radius and ulna are complex and demanding procedures. Whereas several descriptions of complex preoperative planning of long bones of the lower extremity exist [15, 21], only few reports are available concerning the forearm. Blackburn et al. [3] described a percutaneous osteotomy without exact preoperative planning. Others use plain radiographs and image intensifier [14, 19] to control the osteotomy but do not describe exactly how the preoperative planning was performed. Trousdale et al. [24] incorporated CT scans to analyse rotational malunion and proposed three plane correction if necessary. Van Geenen and Besselaar [25] performed osteotomy according to the true plane deformity technique with conventional X-rays. However, it is not described how to manage rotational deformities. Similar to our approach, two computer-assisted methods exist that

Figure 7 Comparison of the computer-assisted approach and conventional planning in case of complex combined angular and rotational deformities. Virtual osteotomies were applied to the 3-d model of the malunited radius according to the results of computer-assisted planning (red) and conventional planning (yellow), respectively. The mirrored radius of the contralateral side is shown in blue. In case of the computer-assisted 3-d approach, the angular deformity was corrected. The position of the yellow radius indicates that the measurements of conventional planning showed inaccuracies after the virtual osteotomy.

allow to virtually plan forearm osteotomies based on 3-d matching to the contralateral bone [16, 18]. Neubauer requires time-consuming segmentation and the use of a commercial program for registration. Their approach was not evaluated with clinical data. In Murase's work, several steps of the planning are performed manually, resulting in very long planning times of up to 3 h. The quantification of the malunion is based on the calculation of the optimal screw axes while neglecting the translational part. We have observed that this can lead to different results compared to our method which also allows calculating the optimal transformation without translation.

Particularly, the determination of the rotational component of the malunion is difficult since only few and less prominent bony landmarks are present which may additionally have a high side-to-side variability [5, 6, 23]. Currently, the most accurate way to determine rotational malunion solely based on CT images is the method described by Bindra et al. [2] where only two axial CT images, one of the region of the bicipital tuberosity and one of the distal radius, are compared by applying lines onto bony edges and planes. Similar slice-based methods which incorporate the bicipital tuberosity and the interosseous bone edges seem to be even less accurate [6]. Others used the orientation of the styloid process of the radius in relation with the bicipital tuberosity on plain radiographs to determine rotational components of malunions [19]. However, the already acquired CT scan offers much more useful information which is not included in the methods described above.

On the basis of two case reports, we describe a computer-assisted volumetric method to determine and quantify a malunion of the radius shaft. The approach is to automatically compare 3-d models of both radii, generated from segmented CT scans of the patient's impaired and healthy forearm. After mirroring one of the radii, both bony parts proximal to the malunion are accurately matched by a registration algorithm. The different alignment of the two distal parts represents the deformation which can be quantified using an optimization algorithm. This obtained information is used for preoperative planning and surgical guidance. The first presented case had a minimal angular and rotational malunion which was difficult to assess on plain radiographs. However, a loss of pronation of 30° compared to the healthy side suggested a mainly rotational malunion. Furthermore, we assumed that the very proximal localisation of the malunion had more influence on ROM as would have been suggested in a mid shaft malunion [13, 20, 23]. Therefore, and due to the fact that a pronation limitation is mainly caused by bony collision in the proximal half of the forearm, we claimed

Figure 8 Three months postoperative radiographs showing the restored anatomical alignment of the radius.

that the analysis and the planning of the osteotomy should be as accurate as possible. In our method, the whole crankshaft shaped proximal part of the radius including the bicipital tuberosity was used to define its position relative to the contralateral bone. The same approach using the entire volumetric data was applied to allocate the distal parts of both radii. This allowed the quantification of the malunion in all three axes. The preoperative planning was based on this information where both angular deformities were transformed to the true plane deformity angle [17] and its axial orientation.

The clinical result of the first case with an improvement of 25° in pronation and pain relief confirms the right direction of our approach although does not clearly prove its necessity. The tool allowed us to calculate the rotational malunion with a volumetric consideration of the proximal part of the radius. Under the assumption that the bony contour of the proximal radius is one of the most important restraints for pronation, it is targeted to reconstruct the ideal shape as given from the contralateral side. In this case, we did not find significant differences in the calculation of the rotational malunion compared to the method of Bindra et al. [2]. However, our approach does not rely on manual measurements based on landmarks that may be sensitive to errors and might be the method incorporating most information. This, however, still has to be confirmed by a study comparing the rotation of both radii in normal subjects.

The second case, although only with a 6-month postoperative follow-up, illustrates that gross angular and rotational deformities combined with multiplanar lateral displacement can be calculated much more exactly compared to conventional planning methods (Figs. 5 and 7). It is currently not possible to intraoperatively correct the deformation stepwise in our approach. The exact rotational deformity can be defined and marked at the beginning of the repositioning, but flexion and extension deformities are still defined and corrected by the shape of the plate. In contrast, the method of Murase et al. [16] incorporates preoperative information by the individual prefabrication of K-wire and cutting guides which are adapted to the surface of the bone. The positions of the guides are thus defined by the shape of the bone. We currently develop a prototype of an intraoperative cutting guide that will be integrated in the presented framework in the future.

The advantage of our system is that planning can be performed in a reasonable short time due to the automation of the processes. The computer-assisted planning of each of the presented cases was carried out in less than 5 min with minimal user interaction. This is significantly below the time needed for conventional planning (60–90 min). Only few individual influencing factors remain, like the manual positioning of the cutting plane for the osteotomy. Furthermore, the computer-assisted 3-d approach facilitates the

planning of complex cases with multiplanar and rotational malunions which are almost impossible to plan conventionally using 2-plane projections on X-rays. A stepwise correction process as obtained from our system, where first rotation and thereafter flexion and extension are aligned, helps the surgeon to control the repositioning manoeuvre.

While the approach seems promising, following limitations have to be considered. The two presented cases did not demonstrate the advantage of this new planning tool regarding an improved functional outcome which has to be proven on a larger series of patients. A further problem is the fact that the morphology of the contralateral and pretraumatic radius may still differ [6]. Therefore, conventional planning was still carried out along with the computer-assisted technique in order to study possible inaccuracies of the traditional method in case of combined deformities. The computer-based approach was useful in quantifying the bony deformity, and there was evidence of inaccurate conventional planning in case of multiplanar deformities as shown in Fig. 7. However, final corrective decisions were made intraoperatively based on the desired rotator motion goals. It is still not possible to incorporate the influence of the ligaments of the distal and proximal radioulnar joint as well as the interosseous membrane and its constraint to pronation and supination in preoperative planning based on the contralateral bone. These effects may not be present until the osteotomy has been performed and the final position of the bone fragments is adjusted. This was the case for the second patient where the plan to derotate the radius by 65° had to be abandoned. Instead a derotation of 45° was performed intraoperatively to achieve the largest functional ROM. Further disadvantage of our approach are the radiation dose and the costs of the required CT scans. A forearm CT scan in the appropriate resolution (31.5 MicroGy/m²) results in approximately 15 times higher dose than a conventional X-ray of the forearm (2 Micro Gy/m²). Moreover, the costs of a CT scan (145 €) are about 4.4 times as high as a conventional X-ray (33 €) in Switzerland. However, it should be noted that current methods for the assessment of rotational malunions, which were described above, also require CT scans.

Future plans are to develop a procedure without incorporating the opposite side, relying on a kinematic simulation of the pronation–supination movement of the concerning bones incorporating the ligaments and the interosseous membrane. The best out of different simulated situations could so be determined. Such a method might be of advantage in cases like the second one described, where the reconstruction of the radius according to the geometry of the opposite side did not lead to an ideal ROM. Prefabricated bone cutting guides and reposition devices would allow an easier and controlled osteotomy and

osteosynthesis in addition. Another important planned step is to make the developed software freely available to the public.

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