Three-Dimensional Corrective Osteotomy for Malunited Diaphyseal Forearm Fractures Using Custom-Made Surgical Guides Based on Computer Simulation

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Introduction

Three-dimensional corrective osteotomy with use of custom-made surgical guides based on computer simulation can provide a good outcome for patients with a malunited diaphyseal forearm fracture.

Clinical studies have demonstrated that corrective osteotomy for malunited diaphyseal forearm fractures remains a challenging procedure. Anatomical correction of angular deformity, achievement of axial alignment, and restoration of the normal lengths of both bones are necessary to achieve a good outcome, but complex three-dimensional (3D) deformities of both forearm bones are difficult to assess accurately with use of radiography or cross-sectional imaging.

We developed a system incorporating a 3D computer simulation program using computerized bone models produced from computed tomography (CT) data, and we successfully achieved 3D anatomical correction using custom-made surgical guides based on computer simulation to treat upper-extremity deformities¹⁻⁵. Traditionally, osteotomies performed in patients ten years of age or older who have had malunion for more than twelve months result in less favorable outcomes^{6,7}. However, use of custom-made surgical guides based on computer simulation resulted in satisfactory restoration of forearm motion in adults with relatively long-standing malunion.

The technique consists of six major steps:

Step 1: Create computer bone models from CT data

Step 2: Evaluate 3D deformity

Step 3: Plan 3D corrective osteotomy

Step 4: Design custom-made surgical guides

Step 5: Operative setup

Step 6: Perform osteotomy using custom-made osteotomy guides

Step 1: Create Computer Bone Models from CT Data

Obtain CT data of both forearms, and create computer models of the bones from CT data.

- Decrease radiation exposure as much as possible during CT scanning. We use a low-radiation-dose technique (scan time, 0.5 s; scan pitch, 0.562:1; tube current, 10 to 30 mA; tube voltage, 120 kV)⁸ with the patient in the prone position, the shoulder in full elevation, the elbow in full extension, and both limbs overhead.
- Create 3D bone models of the entire radius and ulna bilaterally from the CT data (Fig. 1) using commercially available software (BoneViewer; Ortho3D, Osaka, Japan).

Step 2: Evaluate 3D Deformity

Evaluate the 3D deformity by comparing the affected bone with the mirror image of the contralateral, normal bone (Video 1).

- Superimpose one end of the affected bone onto the corresponding part of the mirror image of the contralateral, normal bone (Fig. 2-A), using commercially available software (BoneSimulator; Ortho3D).

- Superimpose the other end of the affected bone onto the corresponding part of the mirror image of the contralateral, normal bone (Fig. 2-B). Then the deformity is defined in terms of rotation and translation along the deformity axis, which are automatically calculated by the software from the distance between the mirror image of the normal bone and the image of the affected bone superimposed proximally to distally (Fig. 2-C).

Step 3: Plan 3D Corrective Osteotomy

Simulate the 3D corrective osteotomy on the basis of information obtained from the deformity evaluation (Fig. 3).

- When the deformity axis is found to run along the concave side of the deformity, simulate a closing osteotomy after the removal of a wedge of bone (Fig. 4-A). When the deformity axis runs along the convex side, simulate an opening wedge osteotomy followed by wedge-shaped bone-grafting (Fig. 4-B). When the deformity axis is nearly parallel to the longitudinal bone axis, simulate a rotational osteotomy in the osteotomy plane perpendicular to the deformity axis (Fig. 4-C)¹.

Step 4: Design Custom-Made Surgical Guides

Design custom-made surgical guides to reproduce the preoperative simulation during the actual surgery.

- Determine the location of two sets of Kirschner wires parallel to each other on the reduced bone.
- Design the reduction guide with guiding holes for these parallel Kirschner wires using commercially available software (Magics RP; Materialise, Leuven, Belgium) (Fig. 5-A).
- Calculate the location of the Kirschner wires on the deformed bone (Fig. 5-B). The angle of the two sets of Kirschner wires on the deformed bone is equal to the deformity angle.
- Design the osteotomy guide with guiding holes for the Kirschner wires and osteotomy slits to fit closely to the deformed bone surface (Fig. 5-C).
- For patients with both radial and ulnar malunions, perform the same procedure in both bones (Figs. 5-D and 5-E).
- Check the entire appearance of both bones, including the bone length after the osteotomy. When there is a discrepancy between the

lengths of the ulna and radius, consider additional shortening or lengthening of the bone.

Step 5: Operative Setup

Manufacture custom-made surgical guides to reproduce the preoperative simulation during the actual surgery.

- Create these surgical guides as plastic models using rapid prototyping technology (Nakashima Medical, Okayama, Japan) with medical-grade resin (Fig. 6).

Step 6: Perform 3D Osteotomy Using Custom-Made Osteotomy Guides

Perform the osteotomy using the custom-made osteotomy guides and achieve anatomical correction using the reduction guides (Videos 2 and 3).

- Expose the radial and ulnar diaphyses through separate incisions.
- Place the osteotomy guide on the planned bone surface.
- Make sure that the distance between the guide and any anatomical landmark (e.g., the tip of the radial styloid) is identical to the preoperative simulation.
- Carefully ensure the placement by checking that all edges of the guide exactly contact the bone surface.
- Fix the osteotomy guide with Kirschner wires inserted through metal sleeves mounted on the guide (Fig. 7-A).
- Perform the osteotomy with a bone saw through the cutting slits in the guide (Figs. 7-B and 7-C).
- Reduce the bones using a reduction guide while maintaining the Kirschner wires in a parallel position (Figs. 7-D and 7-E). For patients with both radial and ulnar malunions, reduce the bones after completion of the osteotomy of both bones.
- Release the interosseous membrane if the planned correction is not achieved.
- Accomplish internal fixation with a plate and screws (Fig. 7-F).

Results

In our series of twenty patients⁹, the average radiographic deformity angle preoperatively was 21° (range, 12° to 35°) compared with that of the normal arm; this improved to 1° (range, 0° to 4°) postopera-

tively (Figs. 8-A and 8-B). In the eighteen patients with a restricted preoperative range of forearm motion, the mean arc of forearm motion improved from 76° (range, 25° to 160°) preoperatively to 152° (range, 80° to 180°) postoperatively.

What to Watch For

Indications

- Malunited diaphyseal forearm fractures with symptoms such as a functional loss of rotation of the forearm and/or painful recurrent dislocation of the ulnar and/or radial head.
- Patients ten years of age or older at the time of surgery

Contraindications

- Bilaterally affected cases.
- Marked shortening of the bone requiring gradual lengthening.

Pitfalls & Challenges

- Soft-tissue contractures or instability of adjacent joints should be checked clinically because they cannot be predicted by 3D bone models alone.
- The decision to apply the technique to long-standing malunions in patients who were less than ten years of age at the time of the initial injury should be made on a case-by-case basis after careful review of the entire bone deformity, including the adjacent joints. Bone deformity is often complicated by remodeling in these cases.
- Active remodeling of the bones and improvement of forearm motion can be expected in patients younger than ten years of age.

Clinical Comments

- Should ligament repair or reconstruction be performed in patients with instability of the distal radioulnar joint?
- Should the interosseous membrane be released simultaneously?

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Figures

Fig. 1

The bones are segmented on the computer, and 3D computer bone models are created.

Fig. 2-A

The distal side of the affected bone (yellow) is superimposed onto the mirror image of the contralateral, normal bone (translucent white).

Fig. 2-B

The proximal side of the affected bone (yellow) is superimposed onto the mirror image of the contralateral, normal bone (translucent white).

Fig. 2-C

The 3D deformity axis (asterisk) and deformity amount are automatically calculated by the software from the distance between the mirror image of the normal bone and the image of the affected bone superimposed proximally to distally.

Fig. 3

The bent cylinders represent the deformed bones. Different deformities can show a similar silhouette (the left figures of A, B, and C). The three-dimensional relationship between the bone and the deformity axis (arrowhead of each figure) suggests the most appropriate method of correction. (Reprinted from: Murase T, Oka K, Moritomo H, Goto A, Yoshikawa H, Sugamoto K. Three-dimensional corrective osteotomy of malunited fractures of the upper extremity with use of a computer simulation system. *J Bone Joint Surg Am.* 2008 Nov;90[11]:2375-89.)

Fig. 4-A

In this case, the deformity axis (asterisk) runs along the concave side of the deformity. A closing osteotomy is appropriate to obtain anatomical reduction. The location of the deformity axis is automatically determined by the computer program and visualized on a monitor.

Fig. 4-B

After removal of a wedge of bone, the distal side of the bone can be reduced by rotating around the axis. The angle of the wedge of bone is equal to the deformity angle around the deformity axis (asterisk).

Fig. 4-C

The reduced bone (yellow) and mirror image of the contralateral normal bone are now well matched to each other.

Fig. 5-A

The location of two sets of Kirschner wires parallel to each other is first determined on the reduced bone. Reduction guides are designed to maintain the Kirschner wires in a parallel position. At surgery, reduction is complete when the Kirschner wires are aligned in a parallel position.

Fig. 5-B

The location of these Kirschner wires is calculated on the deformed bone.

Fig. 5-C

Design of the custom-made osteotomy guide with guiding holes for Kirschner wires and osteotomy slits. The slits accurately guide the bone-saw blade and Kirschner wires inserted through the drill-holes.

Fig. 5-D

For patients with both radial and ulnar malunions, osteotomy is simulated for both bones. Custom-made guides are also produced for both bones.

Fig. 5-E

After reduction, a nearly normal appearance of the bones is obtained. No length discrepancy between the two bones is present.

Fig. 6

The osteotomy guide is manufactured as a plastic model (left: the surgeon's side, right: the bone-contacting side).

Fig. 7-A

The osteotomy guide is fixed onto the surface of the bone.

Fig. 7-B

Osteotomy is performed with use of the cutting slits in the guide.

Fig. 7-C

The bone is divided just as simulated.

Fig. 7-D

For patients with both radial and ulnar malunions, osteotomies of both bones are performed before reduction of the bones.

Fig. 7-E

Both bones are reduced with use of the reduction guides while maintaining the Kirschner wires in a parallel position.

Fig. 7-F

Internal fixation is accomplished with a plate and screws.

Fig. 8-A

Preoperative radiograph of the forearm showing a malunited both-bone fracture of the forearm.

Fig. 8-B

Postoperative radiograph showing good anatomic correction of both bones.

Fig. 1

Fig. 2A

Fig. 2B

Fig. 2C

Fig. 3

Fig. 4A

Fig. 4B

Fig. 4C

Fig. 5A

Fig. 5B

Fig. 5C

Fig. 5D

Fig. 5E

Fig. 6

Fig. 7A

Fig. 7A

Fig. 7C

Fig. 7D

Fig. 7E

Fig. 7F

Fig. 8A

Fig. 8B