Original Article

Corrective osteotomy in symptomatic clavicular malunion using computer-assisted 3-D planning and patient-specific surgical guides

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ABSTRACT

Surgical correction of a symptomatic clavicular malunion requires simultaneous adjustment of the translation as well as the rotation in multiple planes. We describe a corrective osteotomy for a clavicle malunion using 3-D computer assisted preoperative-planning combined with patient-specific surgical guides, along with the benefits and disadvantages of this approach. This method enabled quantifying the malunion by comparing the malunited bone with the normal contralateral clavicle as a template. The postoperative results were encouraging with symmetrical shoulder anatomy and functional improvement. Therefore, we recommend this technique in patients with a symptomatic clavicle malunion, as it allows successful correction of the deformity.

1. Introduction

Clavicle fractures are one of the most common fractures of the shoulder girdle and have an incidence of 5% of all fractures in adults.¹ Between 69%–82% of the clavicle fractures are midshaft, most of them having a good functional outcome after nonoperative treatment.² However, around two-third of all fractures eventually develop some degree of malunion in terms of shortening, malalignment and angular deformity,¹ which can affect the function of the shoulder girdle. Symptoms of a malunited clavicle are often described as persistent pain, rapid muscle fatigue, weakness and loss of shoulder function.^{3–7} Moreover there is often an esthetic component with shortening and “ptosis” of the shoulder. Although an osteotomy that simply corrects the length can improve some of these symptoms, it is important to note that apparently some degree of residual shoulder dysfunction is expected postoperatively if not performed correctly.^{8,9} Although all publications specifically addressing clavicle osteotomies did report improvement, none of these patients had a normal shoulder outcome score. Intuitively, it seems that the best outcome possible can only be expected with correction of the deformities on all planes. However, quantification of the malunion is often difficult to assess in conventional 2-D images because of the 3-D nature of the deformity.

Therefore, in recent years, 3-D preoperative planning has become popular. This technique is already well-established and commonly performed in reconstructions of the hand, the forearm, the humerus, tibia plateau malunions and tibial osteotomies.^{10–12} In these approaches, the contralateral unaffected side is often used as template in

planning a corrective osteotomy for 3D reconstruction. However, when using the contralateral side as a reference, it is obvious that the correction cannot be improved more than the preexistent bilateral asymmetry allows. Hingsammer and coworkers¹³ investigated the bilateral asymmetry for the clavicle in a cadaver study and showed that the left and right clavicles only showed small 3D differences and therefore could be used as mutual reference in preoperative planning.

We recently published our data analyzing the pre- and postoperative radiological result of computer-assisted 3D planned corrective osteotomy in a series of patients with a malunited radius and assessed postoperative function.¹⁴ The obtained results indicated an amelioration of the alignment and the function. Though we have expertise in 3-D pre-operative planning of malunited distal radius fractures, we have not used this procedure for clavicle surgery. The use of computer assisted planning and patient specific cutting guides in corrective osteotomy in symptomatic midshaft clavicular malunion was just recently described during the preparation of our manuscript. However, no patient data were provided.¹⁵

Illustrative case 1: A 42-year-old, otherwise healthy man sustained an isolated closed midshaft fracture of the left clavicle after a motor vehicle accident. The clavicle fracture was treated non-operatively at that time. The right-handed construction worker presented eight years later with discomfort during shoulder mobilization, especially abduction, forward elevation and pain while sleeping on the affected side. He had regular symptoms of muscle fatigue and weakness, limiting him in his daily activities. He further expressed his dissatisfaction with the appearance of the clavicular deformity. On examination, he had full

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range of motion, with a visible deformity of the clavicle on the left side. No objective neurovascular deficits were observed. The clavicular deformity was assessed radiographically, which showed a prominent malunion at the midshaft region.

Illustrative case 2: A 53-year-old healthy patient sustained a right-middle-third- comminuted clavicle fracture during a bicycle accident eighteen years ago. At the time of the fracture, he had no apparent complications and had been treated conservatively. Now he presented to us with discomfort in his right shoulder, with pain during daytime activities and while sleeping on the affected side. He works as a judge and experienced weakness with fatigue during his work. Furthermore he had discomfort while carrying his backpack on hiking trips. He was also unhappy with the cosmetic result of the malunited clavicle. Upon examination, the patient was found to have full motor and sensory function of the limb. The clavicle deformity was assessed radiographically using CT.

2. Preoperative planning and surgical technique

Our patients have provided verbal informed consent for their case information and related images to be published. Preoperative planning¹⁶ is based on a shoulder CT scan at routine clinical dosage (Brilliance scanner, Philips Healthcare, Eindhoven, The Netherlands; 120 kV, 165 mAs) in which the affected and contralateral healthy clavicle are visible. The mirrored contralateral bone serves as template in restoring the malunion. Finding the correct alignment of the lateral clavicle segment with respect to the medial segment starts by segmenting the affected clavicle. This results in a 3-D model of the deformed clavicle (Figs. 1 A and 2A). Next, lateral and medial segments are clipped from the model, which exclude the deformity. These segments can be correctly aligned with the mirrored image of the contralateral bone, by point-to-image registration. Once repositioning is quantified, several options exist to perform the planned alignment.

In patient case 1 (Fig. 1) the CT scan (voxel size $0.33 \times 0.33 \times 1.00$ mm) was used to plan correction using an oblique single-cut rotation osteotomy. In this procedure the bone is not cut in a straight way but in an oblique fashion. Then the lateral bone segment is rotated while keeping the bone faces in the osteotomy plane. For this specific patient case, the required rotation of the lateral bone was 37° cranially. This method helps realigning the bone in the coronal, sagittal

and axis planes. The preoperative alignment planning is shown in Fig. 1B and C. In this figure the segmented bone models of the affected bone (red) and the mirrored contralateral healthy bone (green) are medially aligned, hereby visualizing the deformity from approximately the anterior (Fig. 1D) and cranial direction (Fig. 1E). The white segment in Fig. 1B and C shows the lateral segment in the planned position with a much better alignment.

In patient case 2 (Fig. 2) the oblique single-cut rotation osteotomy method required a very steep cut, which was not considered feasible. We therefore used the CT scan (voxel size $0.85 \times 0.85 \times 0.75$ mm) to plan two oblique cuts and to calculate the required rotation of the middle segment with respect to the medial segment and to calculate an additional rotation of the lateral segment with respect to the middle segment. This resulted in the planning as shown in Fig. 2B and C, in which the red bone represents the affected clavicle, the green bone the mirrored contralateral bone and the white bone the planned state which clearly shows a better aligned although slightly shortened clavicle. Again this can be visualized from the anterior (Fig. 1D) and cranial direction (Fig. 1E).

For both patient cases cutting guides were designed and created by additive manufacturing (Amitek, de Meern, The Netherlands). An additional reduction guide was used for case 2. The three bone segments for this particular case fitted into this guide in only once way, hereby helping the surgeon in achieving the planned reduction.

The surgery was performed under general anesthesia. The patient was placed in an upright beach-chair position, and the left shoulder region was draped free. A standard infraclavicular approach was performed. The periosteum was incised sharply and the muscle attachment was separated subperiosteally as an intact layer so that a 2-layered closure could be performed to secure the plate fixation. We preserved the cutaneous supraclavicular nerves crossing the anterior border of the clavicle. The osteotomy guide was fitted closely onto the clavicle bone surface and fixed with 1.6 mm Kirschner wires inserted through the guiding holes in the template. Prior to the osteotomy two 2.0 mm Kirschner wires were placed at a 36° angle in the first patient case. The osteotomy was performed with an oscillating bone saw under cooling. Care was taken to avoid the underlying neurovascular structures. Using the previously placed K-wires as guide wires, the lateral fragment was rotated using a pointed reduction clamp until the guide wires were parallel, hereby achieving the planned reduction. The bone segments

Fig. 1. Preoperative alignment planning. A–C: 3D model of the deformed clavicle: **Green** mirrored contralateral bone **Red** affected clavicle **White** planned state. D–E Zanca view.

Fig. 2. Preoperative alignment planning. A–C: 3D model of the deformed clavicle: **Green** mirrored contralateral bone **Red** affected clavicle **White** planned state. **D–E:** Zanca view **F:** Intraoperative view.

were temporarily fixed with two K-wires. Final fixation was done using a clavicle compression plate (DePuy/Synthes/Johnson&Johnson, Amersfoort, the Netherlands). A standard closure was performed in layers, and the arm was placed in a sling. The patient began pendulum exercises immediately postoperatively. At 4 weeks full range of motion was initiated. Resisted and strengthening exercises were allowed at 6 weeks.

The surgical procedure in the second case was similar as described above, however, here we performed a double clavicle osteotomy. Reduction was achieved by application of the reduction guide (Fig. 2F). A Variable Angle Clavicle plate (DePuy/Synthes/Johnson&Johnson, Amersfoort, the Netherlands) was used for fixation.

The postoperative course was uneventful for both our patients and they were satisfied with the appearance and symmetry of the shoulder. There was no pain and good muscle strength. Radiologic examination showed that the osteotomies were healed at 6 weeks. Our patients resumed their respective jobs 3 months postoperatively.

3. Discussion

In this report, we describe the technique of a corrective osteotomy of the clavicle using 3-D computer-assisted planning combined with patient-specific surgical guides. A corrective osteotomy of a malunited clavicle fracture remains challenging as the correction requires realignment of the bone segments in three orthogonal planes. If not performed correctly, the patient may remain symptomatic with a persistent deformity of the clavicle. Several studies have reported 3-D pre-operative planning and the use of patient specific surgical guides in corrective osteotomies to accurately reproduce the preoperative planning during surgery.^{10,17,18}

A limited number of reports have been published on the operative treatment of malunited clavicular fractures.^{5,9,19–22} Furthermore, different results were reported. Although all of them reported good results, there was a large variance of the residual dysfunction. Preoperative 3-D planning and the manufacturing of cutting guides have many advantages. It facilitates the pre-operative understanding of the patient's

anatomy as well as the 3-D appreciation of the malunion deformity. Furthermore, it identifies the amount and degree of correction required, to perform the corrective osteotomy as accurate as possible to minimize the residual dysfunction postoperatively. Also, 3-D imaging is more intuitive and shows details that cannot be observed in conventional 2-D methods. A 3-D model furthermore aids in communication with patients in the clinic and can be used in educational settings.

There are also a few disadvantages of the presented computer-assisted technique worth mentioning. For example, the use of a cutting guide requires a relatively large exposure and stripping of the bone as it is based on the bony contour devoid of any soft tissue. Furthermore, the pre-operative planning also requires a healthy, unaffected contralateral clavicle which serves as a reference. A bilateral clavicle fracture would therefore also limit the preoperative planning procedure. Also, cutting and reduction guides require additional costs for design and also for manufacturing (~€250 per guide).

In conclusion, we can say that computer-assisted 3-D planning and patient-specific surgical guides facilitates performing a complex clavicular osteotomy in a controlled manner. This technique has the potential to improve pre-operative understanding of the patient's anatomy as well as intra-operative accuracy. The clinical outcome in our patients were excellent. Therefore, we recommend this technique in patients with a complex clavicle malunion, with the prospective to facilitate the most accurate correction possible and thereby improving the patient's quality of life. However, prospective clinical trials with a large number of patients are needed to confirm advantages and disadvantages of the procedure and of patient outcome.

Conflict of interest

None.

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