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ORIGINAL STUDY

Virtual 3D planning and patient specific surgical guides for corrective osteotomy of the clavicle : report of three cases

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Although many clavicular malunions result in minimal functional deficit, in some symptomatic cases a corrective osteotomy might be necessary. Recently, computer-assisted surgical planning combined with patient-specific surgical guides was introduced as a powerful technology with the potential to improve the accuracy, efficiency, and consistency of corrective osteotomies, as shown for osteotomies in other anatomical regions. We describe the use of this technique in three cases of clavicular malunion.

Keywords: Malunion; clavicle; osteotomy; patient-specific

INTRODUCTION

Clavicular fractures are common injuries, representing 2% to 5% of all adult fractures (*18*). It is traditionally suggested that clavicle fractures uniformly heal with nonsurgical management and result in good functional outcomes. If any fracture displacement is present, nonsurgical treatment results in some degree of malunion. Whereas many malunions result in minimal functional deficit, recent literature suggests that symptomatic malunion may be more common than previously reported *(1, 4, 7, 10, 12, 13, 16, 20)*. Furthermore, clavicular malunion may also result in brachial plexus compression (thoracic outlet syndrome) *(2, 6, 27)*.

The treatment of symptomatic clavicle malunion may require an osteotomy in order to restore anatomic length and rotation *(3, 5, 14, 21-23)*. Currently, the location and the extent of the osteotomy is based on X-rays of both clavicles. However, based on the experience of the surgeon, the resulting correction is unprecise and possibly insufficient, and sometimes associated with peroperative difficulties such as increased operative time and blood loss. Recently, computer-assisted surgical planning combined with patient-specific surgical guides was introduced as a powerful technology with the potential to improve the accuracy, efficiency, and consistency of corrective osteotomies as shown for osteotomies in other anatomical regions *(24-26)*. We describe the use of the technique in three cases of clavicular malunion.

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SURGICAL TECHNIQUE

For three cases of symptomatic malunion, a CT scan of both clavicles was obtained. With the use of Mimics® software (Materialise N.V. Leuven, Belgium) the CT images were segmented and virtual 3D clavicles were created for both the deformed and contralateral clavicles (Fig. 1).

These 3D computer models allow post-scan processing, 3D annotation and measurements as well as visualization from different angles. The contralateral clavicle serves as the template to be matched by the malunited clavicle after the osteotomy (Fig. 2).

Consequently, the Mimics® software (Materialise N.V. Leuven, Belgium) is used to create a virtual model in order to restore ad integrum the pre-fracture anatomy of the malunited clavicle (Fig. 3).

Then, a virtually selected fixation plate system (we used Depuy-Synthes® Clavicle plates™) is aligned and if necessary virtually bent to the planned surgical position. The plate's screw positions and lengths are calculated based on the 3-D model. Relevant angles and distances are noted on the operative plan for later use as a reference during surgery.

In a next step, one or more surgical guides are designed and constructed to match the pre-operative bone geometry and provide guidance for the osteotomy and the computed drill-hole locations (Fig. 4).

The position of the head of the patient during surgery can be taken into consideration for planning

Fig. 1. — Pre-operative situation – image of case 1.

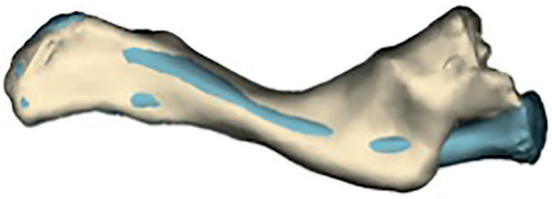

Fig. 2. — The clavicle of the surgical side with the healthy mirrored clavicle (in blue) – image of case 1.

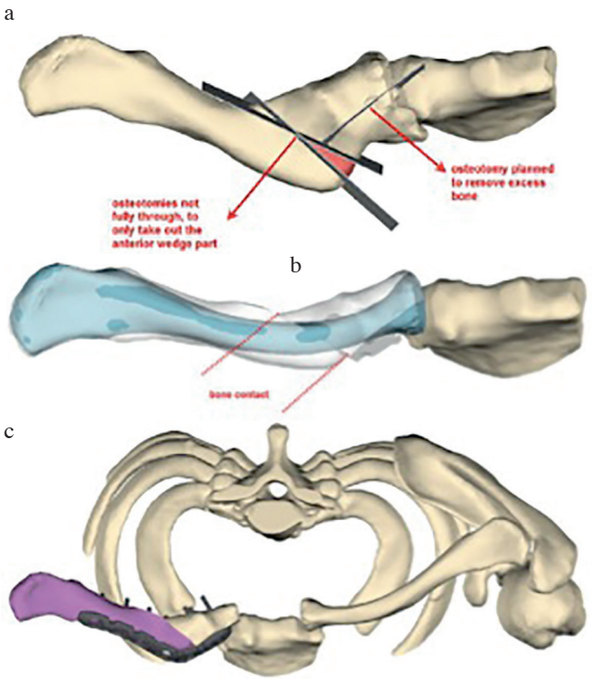

Fig. 3. — (a) The surgical side with the planned resection planes, (b) the mirrored healthy clavicle (in blue) and the resected bone fragments of the surgical side (transparent), (c) the planned fragments of the surgical side and the planned plate position – images of case 1.

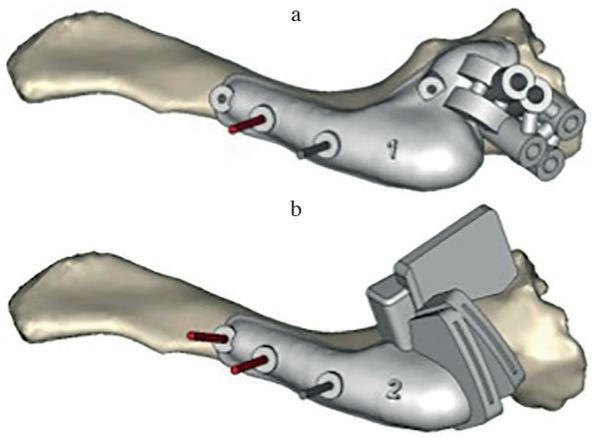

Fig. 4. — (a) Guide for drilling the screw holes, (b) guide for making the osteotomies – images of case 1.

of the location of the drill holes, to avoid difficulties in drill placement. The guide is designed to fit in a unique way on a specific spot on the bone that facilitates guide positioning during surgery. Template models of fixation plates are made in case pre-operative manipulation or bending of the plates is required. Drill guides are placed in the osteotomy guide to match the pre-operative screw positions and orientations. Small openings for K-wires are added in order to fix the guide on the bone.

The surgery is performed in beach chair position under general anesthesia, the head in slight hyperextension and turned to the opposite side. The clavicle is exposed using a longitudinal incision in the usual fashion and the guide is fixed on the bone using K-wires, facilitated by the morphology of the malunion itself. This allows pre-drilling the screw holes through the cylinders of the guide. The osteotomy is then performed via the captured cut slot, and is initiated with the cooled oscillating saw, using a 0.4 mm blade. In case biplanar corrections are necessary, a wedge is removed from the clavicle. Next, the fixation plate is inserted and fixed with cortical or locking screws placed through the pre-drilled holes. A final check of the osteotomy and plate positions is obtained with fluoroscopy and the wound is closed in layers.

CASE-REPORTS

Case 1

A 28 year old right handed worker contacted our department because of weakness and pain in his right shoulder, which was exacerbated by repetitive and resisted activity. He had sustained a right comminuted medial clavicle fracture one year before in a traffic accident. It was treated nonoperativly and went on to malunion.

On presentation to our office, he reported rapid fatigability and difficulty with prolonged activity at work, and with recreational pursuits. He also felt that the appearance of the shoulder was unacceptable/improper. He didn't show any neurological symptoms.

Pre-operative clinical evaluation showed a shortening of the clavicle with a medial prominent clavicle, a more internally rotated, downward rotated and posterior titled scapula and a normal passive range of motion of the glenohumeral joint. During active range of motion, there was asymmetrical scapular movement and a restriction to 160° of flexion and abduction. There was normal active internal and external rotation. Pre-operatively a Constant-Murley score, Oxford score and Quick DASH score was obtained (Table 1).

Table 1. —Pre- and postop follow-up case 1

	pre-op	3 months postop	6 months postop	1 year postop
CS	67	89	91	91
DASH	47	12	4	0

Pre-operative X-ray showed a malunion at the medial 1/3 of the clavicle. A CT scan was obtained using the Mimics system® (Materialise N.V. Leuven, Belgium) protocol (Fig. 1). Drilling and cutting guides were fabricated for corrective osteotomy that was planned to elongate the clavicle by 13 mm (from 112 to 125 mm), derotate it 18° (rotation difference pre-op 33°, postop 15°) in the sagittal plane and straighten the angulation deformity left by the malunion. The osteosynthesis was performed using a clavicular plate (Depuy-Synthes LCP Superior Anterior Clavicle Plate 2.7/3.5 with lateral extension, 5 holes, right). The operation was performed as planned and the patient was allowed to start active mobilization on post operative day one. The patient recuperated quickly, with no complaints or complications (Table 1).

At 6 weeks post-operatively X-rays showed signs of consolidation. At 3 months post-operatively, a CT scan showed complete consolidation of the corrective osteotomy.

At one year follow-up, clinical examination showed pain free 180° shoulder flexion and abduction (Table 1). At rest the patient had normal scapular position. Thoracoscapular dyskinesia was still present during active range of motion but less pronounced compared to the pre-operative situation. Currently, the patient is doing all daily and recreational activities without problems. He does not complain of hardware irritation.

Case 2

A 44 year old left-handed bus driver was the victim of a motorbike accident. Beside other injuries, this polytraumatized patient suffered a complex injury of his left upper extremity which included costal fractures, a mid-clavicular fracture, and brachial plexus palsy. All fractures were closed except the forearm fracture. The non-operated clavicular fracture healed within six weeks in a malunited position that was judged acceptable. All other fractures, which had been internally fixed, healed in the expected time durations, with some minor complications.

Three months after the trauma, the patient still presented a major palsy of his upper extremity, although he had recovered some function (M4) in his shoulder internal rotators, biceps and triceps, in his fingers' flexion and abduction/adduction. Horner's sign was negative. Magnetic resonance imaging (MRI) did not show a pseudomeningocele. A surgical exploration of the brachial plexus was therefore performed. No root avulsion was found, but the C5 root and the suprascapular nerve were fibrotic and not stimulable. A huge clavicular callus compressed the brachial plexus. Further distally the axillary nerve was not stimulable; the radial and median nerves were stimulable, but only with high electrical amplitudes. A simple neurolysis was performed, and there was no attempt at removing the clavicular callus. The patient subsequently recovered all sensibility and motor function, except for the radial nerve functions, presumably more distally injured at the level of the humeral fracture.

Six years after the trauma, the patient consulted for dysesthesiae in his ring and little fingers, exacerbated at night. Tinel's sign was present in the suprascapular space as well as along the median and ulnar nerves in the forearm. Pre-operatively a Constant-Murley score, Oxford score and Quick DASH score were obtained (Table 2). There was no objective motor nor sensory deficit. After exclusion of compression of the ulnar or median nerve at elbow or wrist, the workup focused on the compression of the previously traumatized brachial plexus by the malunited clavicle. In particular, a MRI clearly demonstrated the angulated clavicle impinging on the brachial plexus.

The patient had therefore a clavicular osteotomy performed after virtual 3D planning (Fig. 5) and with the use of patient-specific surgical guides.

Compared to the contralateral clavicle, the clavicle was elongated 4 mm (from 159 mm to 163 mm), rotated 14° in sagittal plane (rotation difference pre-op 25°, postop 11°) and angulated 21° in the sagittal plane (difference pre-op 28°,

Table 2. — Pre- and postop follow-up case 2

	pre-op	3 months postop	6 months postop	1 year postop
CS	19	25	37	58
DASH	79	60	52	48
Oxford	14	18	24	24

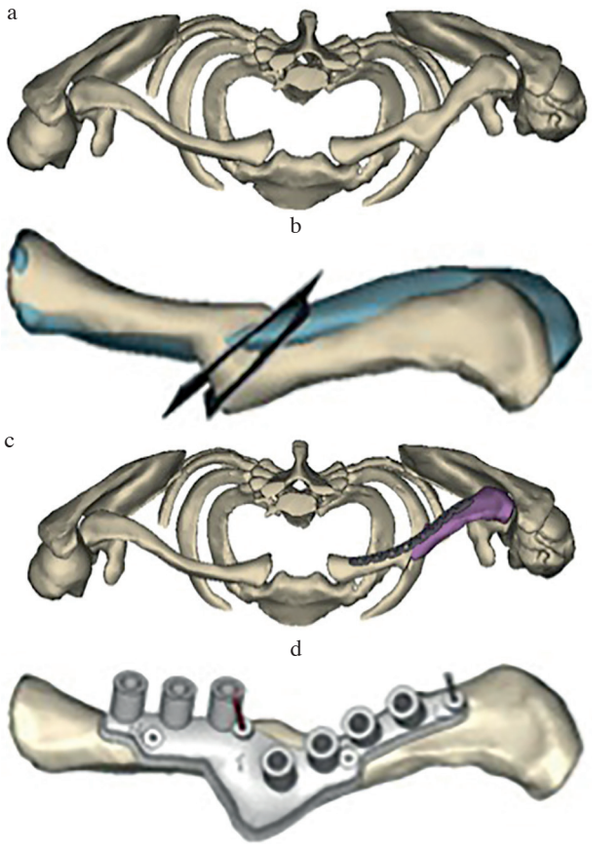

Fig. 5-6. — (a) Pre-operative situation blue, (b) planned outcome, (c) planned resections. The mirrored healthy side is depicted in blue, (d) planned outcome.

difference postop 7°) and 16° in the coronal plane (difference pre-op 22°, difference postop 6°). The osteotomy included removal of a bone wedge which was morcellized and used as a bone graft, disposed around the osteotomy site. The osteosynthesis was performed using a slightly bent low-contact locked clavicular plate (Depuy-Synthes LCP Superior Clavicle Plate 3.5, 8 hole, left). No attempt was done to neurolyse the brachial plexus.

Immediately after the surgery, the patient had total disappearance of his dysesthesiae. At 9 months postoperatively, X-rays showed signs of consolidation. The patient's dysethesiae did not returned (Table 2).

Case 3

A 29-year-old left hand dominant structural engineer came for medical consultation four years after fracturing his right clavicle while playing football. He did reasonably well for two years, but noticed that he had had increasing pain at both the acromioclavicular and sternoclavicular joints during activity for the past two years. He pointed to his mid-clavicle and along his sternum when asked specifically where his pain was located. He felt like it was getting worse and that his involved shoulder was "shorter than the other one." He had tried physical therapy, special stretches, multiple cortisone shots, and was on regular NSAIDS without relief.

The physical examination revealed a modest bony deformity with the apex of the malunion anterior and superior in the mid clavicular region. Full AROM and PROM of the glenohumeral joint was present, with good strength to resisted testing. He had no complain of parasthesiae and was neurovascularly intact (Table 3). In office X-rays confirmed the malunion.

Table 3: pre- and postop follow-up case 3

	pre-op	3 months postop	6 months postop	1 year postop
CS	40	60	78	82
DASH	41	20	18	4
Oxford	33	42	42	46

He underwent preoperative computed tomography (CT) scanning of both clavicles (Fig. 6) for pre-operative planning in Mimics, and then the osteotomy, drilling and cutting guides where manufactured.

A Synthes 3.5 congruent clavicular plate (Synthes 2.7 mm/3.5 mm VA-LCP lateral anterior clavicle plate) was to be used without any preoperative bending. The clavicle was elongated 13 mm (from 141 mm to 154 mm), no rotation and angulated 5°

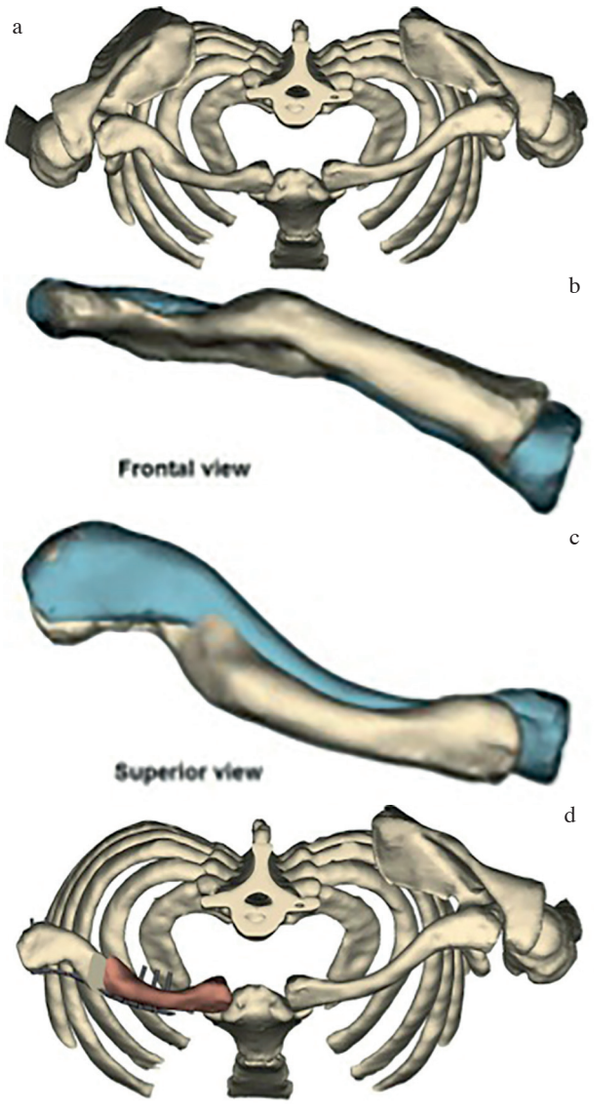

Fig. 6. — (a) Pre-operative situation blue, (b) planned outcome, (c) planned resections. The mirrored healthy side is depicted in blue, (d) planned outcome.

in the sagittal plane (difference pre-op 7°, difference postop 2°). At three months postoperatively, X-rays confirmed healing of the osteotomy.

The patient had no complains of pain with sports or other activities (Table 3). He currently has no hardware complaints and has no plan to remove his plate.

DISCUSSION

Malunion, a common finding after conservative treatment of clavicular fractures *(15)*, is defined as a healed fracture in a non-optimal position. This may result in shortening, rotation, angulation of the clavicle, or a combination thereof. However, in literature, when describing malunion of the clavicle only the shortening is evaluated, rotation and the angulation are ignored *(11, 15)*.

Because of the closed chain effect related to the thorax–scapula–clavicle complex, malunion of the clavicle will cause changes in the shoulder girdle with altered movements. It will change the starting position of the scapula, the scapular kinematics and completely alter shoulder biomechanics *(8, 17, 19)*. Currently, it is not clear for which patients a malunion has clinical consequences. The combination of the structural lesion and the physical demands of the individual patient influences the subjective outcome of a malunion of the clavicle.

If conservative treatment fails in case of symptomatic malunion, a corrective osteotomy can be performed *(12)*. A corrective osteotomy of a healed clavicle is only acceptable in our opinion if the surgery allows an adequate restoration of the clavicular anatomy, correcting shortening, angulation and rotation as good as possible *(12)*. This is facilitated by 3D pre-operative planning and by the use of prefabricated guides. Because of the bilateral symmetry of the clavicle, the contralateral side can be used as a template *(9)*. Peroperatively the planned correction can be performed as accurate as possible. Because the drill holes of the screws can be made before the osteotomy, a good and unique fit of the fixation plate after the correction can give the surgeon preoperatively extra information concerning the accuracy of correction. We believe this system can help to obtain a more accurate correction of the clavicular malunion as compared to a traditional corrective osteotomy and that it facilitates the surgery.

CONCLUSION

Virtual 3D planning and patient-specific surgical guides facilitate surgery and contribute to an adequate corrective osteotomy of the clavicle.

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