JSES International 5 (2021) 729–733

Contents lists available at ScienceDirect

JSES International

journal homepage: www.jsesinternational.org

Three-dimensional imaging, modeling, and printing in the correction of a complex clavicle malunion

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ARTICLE INFO

Keywords:
3D
Printing
Traumatology
Clavicle
Fracture
Malunion
3-D image

Although displaced fractures of the middle third of the clavicle have been traditionally treated conservatively, recent studies have shown that surgical management achieves higher union rates and better cosmetic results.[1–6] Thus, current trends consider surgery in cases of a floating shoulder, an open fracture, neurovascular damage, or serious comminution or shortening over 15 mm in active patients.[7,8] However, excessive angulation will only lead to surgical management if the patient is concerned about the cosmetic result. In any case, it is advisable to assess each case individually and to present to the patient all possible options.[9] Some orthopedists opt to initially treat all of these fractures conservatively, delaying the surgery decision for 6 months.[10]

The most common complication of diaphyseal displaced clavicle fractures is malunion, although in most cases, patients present with no symptoms. However, occasionally, malunion leads to functional or neurological impairment, particularly when the shortening is over 20 mm.[11] Surgical correction of such deformities has been demonstrated to improve the symptomatology and satisfaction of patients.[12]

However, the complex geometry of the clavicle hinders planning and execution of these surgeries. Our goal is to describe a methodology that uses three-dimensional (3D) imaging, modeling, and printing to get optimal results with a limited budget.

We report a case of a 33-year-old man who sustained a fracture located in the union between the middle and lateral thirds of the clavicle. The lesion was initially managed conservatively, and it resulted in a malunion. Despite the marked deformity (Fig. 1), which presented deviations in all planes, the reason for consultation was some various clinical symptoms including dizziness, headaches, and scapular pain without a defined mechanical rhythm.

Neurological and vascular causes, as well as cervical pathology, were ruled out as the probable origin of the pain. Therefore, we proposed correction of the deformity by means of an osteotomy and internal fixation, and the patient provided informed consent after being fully informed about the benefits and risks of the procedure.

The correction of clavicle malunions presents issues of particular complexity, which include the following:

- defining the deformity accurately and determining the plane of osteotomy in relation to the apex;
- determining the final positioning of the bone segments;
- reducing the risk of nonunion by increasing the contact area of the osteotomy;
- assessing the implant that will be used and determining its length; and
- being able to reproduce the planning in the operating room and being capable of fixing the bone segments in the desired position.

Preoperative planning is crucial,[12] and due to the complex nature of our case's deformity, we opted to take advantage of our experience with 3D imaging and modeling techniques.[13] We used the techniques to define the deformity, to plan the desired result, and to develop surgical tools that would help us carry out the surgical plan in the most precise way.

Institutional review board approval was not required for this case report.

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https://doi.org/10.1016/j.jseint.2021.04.008

Figure 1 Clinical image of the deformity.

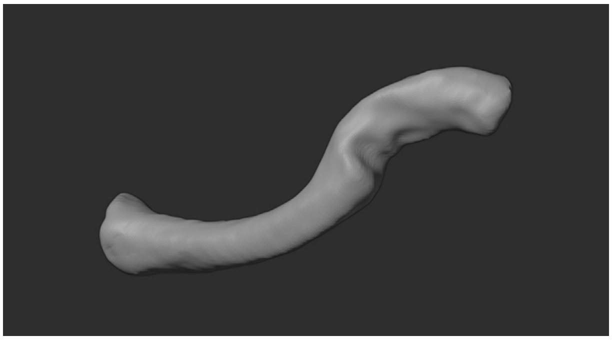

Figure 2 Optimized rendering of the affected clavicle.

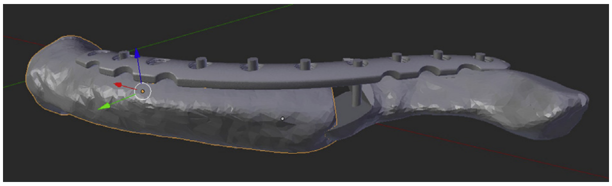

Figure 3 Final planned position of the bone segments and the implants.

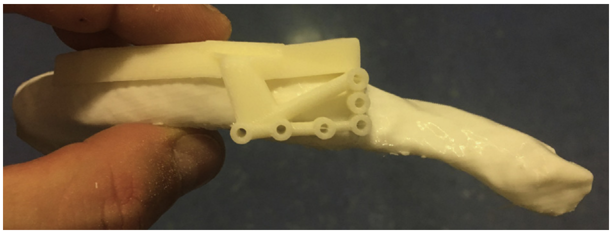

Figure 4 Printed osteotomy guide.

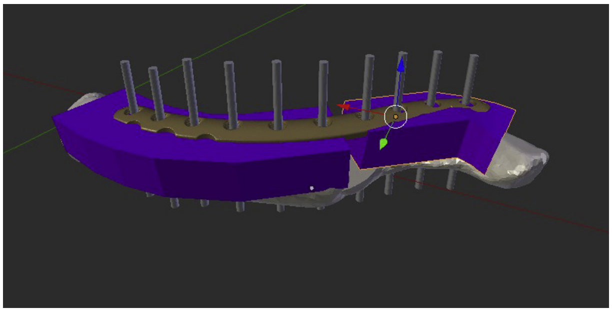

Figure 5 Preparation of the screw guide.

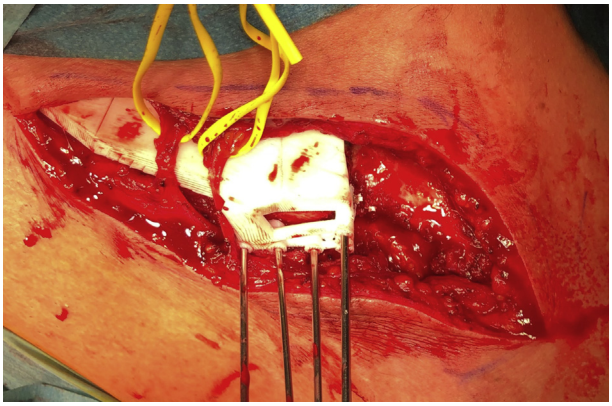

Figure 6 Intraoperatory image showing the use of the osteotomy guide.

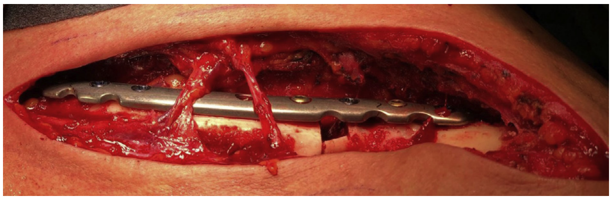

Figure 7 Intraoperatory image showing the final positioning of the bone and the implants.

The first step was to obtain a computed tomography scan in Digital Imaging and Communications in Medicine format that was later processed to generate a 3D model by using the open source software Slicer 3D.[14] Once the basic 3D model was produced, it was optimized by employing the Meshmixer software (Autodesk Inc., Mill Valley, CA, USA) (Fig. 2).

Surgery was planned in a virtual environment by using the Blender software (Blender Foundation, Amsterdam, the Netherlands), although we also printed a physical model of the clavicle to obtain a better understanding of the local anatomy.

To determine the bone morphology prior to the trauma, the contralateral clavicle of the patient was mirrored. Several authors have agreed that the left clavicle is longer than the right clavicle,[15–21] and we decided to use the magnitudes defined by Bertat et al[20] in their 3D anatomical study. As they found that the average difference between both clavicles amounts to 1.8 mm, we scaled our reference bone accordingly.

The deformity apex was defined, and osteotomy was performed at that exact point. The bone cutting would be L-shaped to maximize the contact area and reduce the risk of nonunion. After performing the osteotomy over the virtual bone, the bone segments were displaced to their final position. To do so, the 3D models of both clavicles were superimposed, and an algorithm that minimizes the spatial differences between the points of 2 different meshes (iterative closest point) was applied. During the planning, we applied a digital model of the osteosynthesis plate in the desired position and simulated the screw trajectories (Fig. 3).

However, reproducing the same planning in the real patient is nearly impossible because the operating room lacks references and positioning tools that we have in the digital world.

Figure 8 Workflow of the entire procedure.

To fulfil our aim, patient-specific osteotomy and screw guides were designed and printed. The Blender software was used to model the guides, and in both designs, a negative clavicle was used to obtain an optimal adjustment to the anatomy of the patient. The osteotomy guide was engineered in such a way that it allowed Kirschner wires to be placed in the shape of an L so that they limited oscillating saw movement (Fig. 4). Regarding the screw guide, a Boolean operation was used to subtract the volume of the bone and the screws from a square prism, obtaining a structure in which the base was a mirror image of the clavicle and endowed with holes that would allow the bone screw holes to be drilled in the planned position (Fig. 5).

Both models were exported to the Ultimaker Cura slicer (Ultimaker, Utrecht, the Netherlands) and printed using fused deposition modeling technology. Smartfil ABS Medical (Smart Materials 3D, Jaen, Spain) was employed in printing, as it is specifically designed for medical applications and because its biocompatibility is ensured by the accreditation class USP VI and ISO 10993-1. Ethylene oxide was used to sterilize the guides before surgery.

Surgery was performed using the standard technique;[12] so here, we will only make reference to the particularities of our case. The osteotomy guide adapted well to the clavicle thanks to its negative bone shape, and it allowed for the application of several 1.8 mm Kirschner wires in the shape of an L (Fig. 6). After removing the guide, osteotomy was performed using the wires to guide the oscillating saw. After that, the screw guide was used to drill both segments so that both the fragments and the osteosynthesis plate would be positioned according to the preoperative plan. Medial fragment holes were drilled first, followed by lateral fragment holes. The plate was then secured to the medial part of the clavicle, and the bone was automatically reduced when the screws of the lateral fragment were introduced into the previously drilled holes (Fig. 7).

No complications were detected during the 6-month follow-up, and the radiographs showed good fracture consolidation. The patient is now asymptomatic and happy with the result. He has resumed his previous professional activity, which requires significant physical effort (Fig. 8).

Discussion

This case is interesting because of the methodology applied for its resolution and the use of new imaging technologies to characterize the bone deformity. New 3D modeling technologies were used to plan the surgery and new 3D printing techniques were used to create the surgical tools that allowed the surgical team to obtain a successful result. Although other authors published similar planning methodologies,[22–24] in our case everything was achieved by using open-source software, which means that any surgeon can replicate our procedure (Fig. 9). Also, besides the planning of creating an osteotomy guide, our technique included a drill guide that allows precise fixation of the bone.

Although most displaced middle-third clavicle fractures heal without intervention, those that evolve negatively can improve their prognosis if the malunion is surgically corrected.[12,25,26] The singular anatomy of the clavicle makes angular corrections in that area particularly difficult, but the harnessing of new technologies allows the surgeon to achieve reproducible results through an easier and faster method.[24,27,28]

The use of new 3D technologies to manage challenging orthopedic and trauma cases is gaining ground rapidly,[29,30] and our hospital has incorporated it into daily practice.[13] Of course, its application implies assuming a learning curve and changing the way that different departments cooperate. In our experience, we quantify the time investment for learning to be approximately 1 month of exclusive dedication. Nevertheless, the results that can be achieved with this methodology make the effort worthwhile and we truly believe that it is nearly imperative that modern trauma surgeons incorporate this knowledge into their armamentarium, the same way that radiology and computed tomography scan usage were incorporated back in the day.

Disclaimers:

Funding: No funding was disclosed by the author(s).

Conflicts of interest: The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

Patient consent: Obtained.

Acknowledgments

The authors wish to thank María Rabanal and Pablo Roza for their collaboration in writing the manuscript.

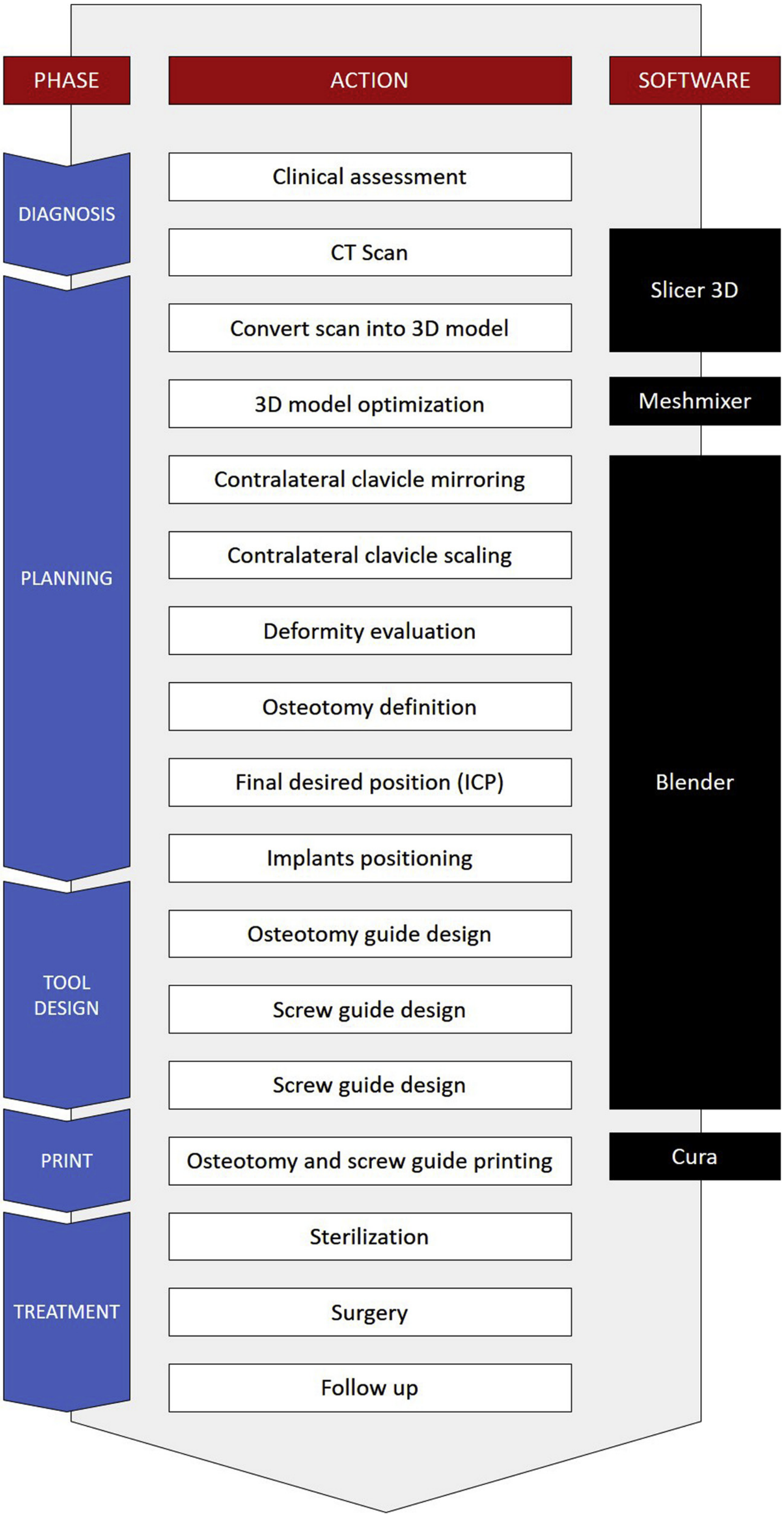

Figure 9 Workflow of the entire procedure.

References

1. Canadian Orthopaedic Trauma Society. Nonoperative treatment compared with plate fixation of displaced midshaft clavicular fractures. A multicenter, randomized clinical trial. J Bone Joint Surg Am 2007;89:1-10. https://doi.org/10.2106/JBJS.F.00020.
2. Denard PJ, Koval KJ, Cantu RV, Weinstein JN. Management of midshaft clavicle fractures in adults. Am J Orthop (Belle Mead Nj) 2005;34:527-36.

3. Nowak J, Holgersson M, Larsson S. Sequelae from clavicular fractures are common. Acta Orthop 2005;76:496-502. https://doi.org/10.1080/17453670510041475.
4. Robinson CM, Goudie EB, Murray IR, et al. Open reduction and plate fixation versus nonoperative treatment for displaced midshaft clavicular fractures. J Bone Joint Surg 2013;95:1576-84. https://doi.org/10.2106/JBJS.L.00307.
5. Guerra E, Previtali D, Tamborini S, et al. Midshaft clavicle fractures: surgery provides better results as compared with nonoperative treatment: a meta-analysis. Am J Sports Med 2019;47:3541-51. https://doi.org/10.1177/0363546519826961.
6. Wang X, Guo W, Li A, et al. Operative versus nonoperative treatment for displaced midshaft clavicle fractures: a meta-analysis based on current evidence. Clinics 2015;70:584-92. https://doi.org/10.6061/clinics/2015(08)09.
7. Ropars M, Thomazeau H, Huten D. Clavicle fractures. Orthop Traumatol Surg Res 2017;103:S53-9. https://doi.org/10.1016/j.otsr.2016.11.007.
8. Lazarides S, Zafiropoulos G. Conservative treatment of fractures at the middle third of the clavicle: the relevance of shortening and clinical outcome. J Shoulder Elbow Surg 2006;15:191-4. https://doi.org/10.1016/j.jse.2005.08.007.
9. Lenza M, Buchbinder R, Johnston RV, et al. Surgical versus conservative interventions for treating fractures of the middle third of the clavicle. Cochrane Database Syst Rev 2019;6:CD009363. https://doi.org/10.1002/14651858.CD009363.pub3.
10. Meunier A. Who should be treated surgically for a displaced clavicle fracture? Acta Orthop 2016;87:539-40. https://doi.org/10.1080/17453674.2016.1247562.
11. Hill JM, McGuire MH, Crosby LA. Closed treatment of displaced middle-third fractures of the clavicle gives poor results. J Bone Joint Surg 1997;79:537-9.
12. Mckee MD, Wild LM, Schemitsch EH. Midshaft malunions of the clavicle. J Bone Joint Surg Am 2004;86:37-43. https://doi.org/10.2106/00004623-200403001-00006.
13. Di Felice Ardente P, Fusaro FM, Abad MP, et al. The utilization of computer planning and 3D-printed guide in the surgical management of a reverse Hill-Sachs lesion. JSES Int 2020;4:569-73. https://doi.org/10.1016/j.jseint.2020.04.013.
14. Kikinis R, Pieper SD, Vosburgh KG. 3D Slicer: a platform for subject-specific image analysis, visualization, and clinical support. In: Intraoperative imaging and image-Guided Therapy. New York, NY: Springer New York; 2014. p. 277-89.
15. Parsons FG. On the proportions and characteristics of the modern English clavicle. J Anat 1916;51:71-93.
16. Mays S, Steele J, Ford M. Directional asymmetry in the human clavicle. Int J Osteoarchaeol 1999;9:18-28.
17. Andermahr J, Jubel A, Elsner A, et al. Anatomy of the clavicle and the intramedullary nailing of midclavicular fractures. Clin Anat 2007;20:48-56. https://doi.org/10.1002/ca.20269.
18. Auerbach BM, Raxter MH. Patterns of clavicular bilateral asymmetry in relation to the humerus: variation among humans. J Hum Evol 2008;54:663-74. https://doi.org/10.1016/j.jhevol.2007.10.002.
19. Danforth ME, Thompson A. An evaluation of determination of handedness using standard osteological measurements. J Forensic Sci 2008;53:777-81. https://doi.org/10.1111/j.1556-4029.2008.00741.x.
20. Bernat A, Huysmans T, Van Glabbeek F, et al. The anatomy of the clavicle. Clin Anat 2014;27:712-23. https://doi.org/10.1002/ca.22288.
21. Daruwalla ZJ, Courtis P, Fitzpatrick C, et al. Anatomic variation of the clavicle: a novel three-dimensional study. Clin Anat NA-NA 2010;23:199-209. https://doi.org/10.1002/ca.20924.
22. Haefeli M, Schenkel M, Schumacher R, Eid K. Corrective osteotomy for symptomatic clavicle malunion using patient-specific osteotomy and reduction guides. Tech Hand Up Extrem Surg 2017;21:91-100. https://doi.org/10.1097/BTH.0000000000000161.
23. Van Tongel A, De Wilde L, Huish S, Schuind F. Virtual 3D planning and patient specific surgical guides for corrective osteotomy of the clavicle: report of three cases. Acta Orthop Belg 2017;83:297-303.
24. Roner S, Bersier P, Fürnstahl P, et al. 3D planning and surgical navigation of clavicle osteosynthesis using adaptable patient-specific instruments. J Orthop Surg Res 2019;14:115. https://doi.org/10.1186/s13018-019-1151-8.
25. Martetschläger F, Gaskill TR, Millett PJ. Management of clavicle nonunion and malunion. J Shoulder Elbow Surg 2013;22:862-8. https://doi.org/10.1016/j.jse.2013.01.022.
26. Der Tavitian J, Davison JNS, Dias JJ. Clavicular fracture non-union surgical outcome and complications. Injury 2002;33:135-43. https://doi.org/10.1016/S0020-1383(01)00069-9.
27. Roner S, Vlachopoulos L, Nagy L, et al. Accuracy and Early clinical outcome of 3-dimensional planned and guided Single-Cut Osteotomies of Malunited Forearm bones. J Hand Surg Am 2017;42:1031.e1-8. https://doi.org/10.1016/j.jhsa.2017.07.002.
28. Miyake J, Murase T, Oka K, et al. Computer-assisted corrective osteotomy for Malunited diaphyseal Forearm fractures. J Bone Joint Surg 2012;94:e150. https://doi.org/10.2106/JBJS.K.00829.
29. Vaishya R, Patralekh MK, Vaish A, et al. Publication trends and knowledge mapping in 3D printing in orthopaedics. J Clin Orthop Trauma 2018;9:194-201. https://doi.org/10.1016/j.jcot.2018.07.006.
30. Lal H, Patralekh MK. 3D printing and its applications in orthopaedic trauma: a technological marvel. J Clin Orthop Trauma 2018;9:260-8. https://doi.org/10.1016/j.jcot.2018.07.022.