Technical Note

Step-Cut Clavicle Osteotomy and T-Shaped Iliac Crest Graft for Clavicle Nonunion Using 3-Dimensionally Planned Custom-Made Surgical Guides and Plate Fixation

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Abstract: Clavicle fractures are common, with nonunion rates reaching up to 31% without surgery. Surgical treatment with plate fixation and iliac crest autograft enhances healing, yet accurate reconstruction remains challenging owing to clavicular morphology. This study presents a surgical technique using virtual surgical planning to create 3-dimensionally printed patient-specific surgical guides and a custom-made clavicle plate. This approach enables precise osteotomies, optimal graft shaping, and accurate anatomic reconstruction. The T-shaped autograft provides enhanced stability and increased bone contact, while the custom plate facilitates compression and interfragmentary fixation.

Clavicle fractures are common, with the majority occurring in the midshaft region, followed by the lateral end. Although healing is the most frequent scenario, midshaft nonunion rates of up to 31% occur without surgery and are reduced to 5.9% with surgical intervention.[1,2] Some contributing factors include fracture displacement, comminution, older age, smoking, and female sex.[3-5] Nonunion may lead to pain, limited mobility, muscle weakness, sleep disruption, and altered scapulohumeral mechanics due to clavicular shortening.[6]

Surgical treatment of clavicle nonunion typically involves open reduction and plating fixation, with autologous cortical bone grafts generally obtained from the iliac crest used to address segmental bone loss. This procedure has shown a high rate of bone union.[7,8] Restoring the length of the clavicle is important to avoid disturbances in scapular and glenohumeral kinematic patterns, as well as cosmetic deformity.[9] For this purpose, careful planning of nonunion resection and bone graft shaping is crucial, but to date, freehand bone harvest with fixation is the standard way of treatment.[7-9]

A recent article described a surgical technique for congenital pseudarthrosis of the clavicle using a T-shaped autograft to increase stability of the fixation and surface area for bone-to-bone healing.[10] However, calculating the dimensions and shape of the bone recipient site and bone autograft, as well as plate adaptation to the reconstruction, may be challenging owing to the tortuous surface of the clavicle.

We present the surgical technique of step-cut clavicle osteotomy and T-shaped iliac crest graft for clavicle nonunion using virtual surgical planning (VSP) to produce custom-made surgical guides and plate fixation. This approach aims to enhance clavicle osteotomy and graft harvest precision to achieve a stable and anatomic bone reconstruction, referencing the contralateral clavicle.

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Surgical Technique

Patient Evaluation, Imaging, and Indications

In case of clavicle nonunion, the patient should be asked about the injury mechanism, his or her medical history, and any medications that could affect bone consolidation. The elapsed time after the primary fracture is critical, with nonunion typically considered when consolidation has not occurred by 6 months.

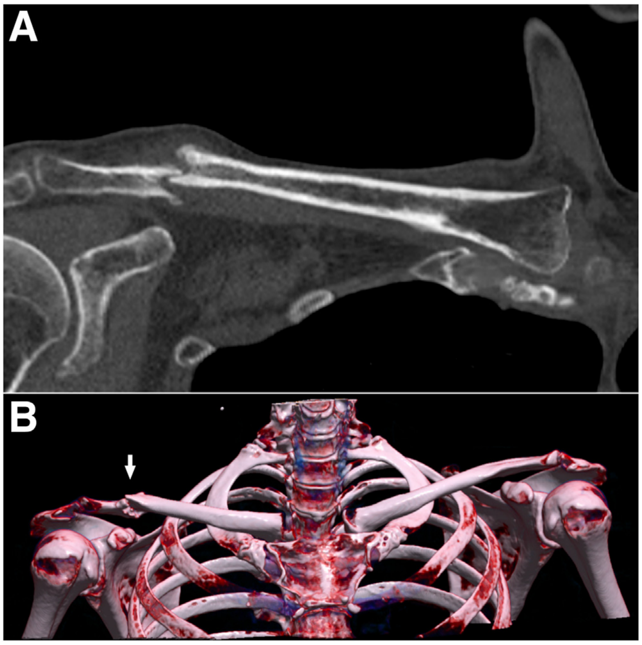

Fig 1. Preoperative imaging of right shoulder. (A) Two-dimensional computed tomography scan, coronal slice, highlighting selected focus of atrophic nonunion. (B) Three-dimensional computed tomography reconstruction comparing both clavicles. The right clavicle is pathological. The arrow indicates the nonunion site.

Careful assessment of the patient's functional limitations, range of motion, and inability to perform daily activities should be recorded. The imaging examination should include serial radiographs without evidence of bone consolidation, and when surgery is indicated, a computed tomography (CT) scan should be obtained to confirm clavicle nonunion, as shown in Figure 1.

Prior to surgical intervention, VSP based on bilateral 3-dimensional reconstruction of the CT imaging can be performed. The healthy contralateral clavicle is mirrored and serves as a reconstruction template to calculate the appropriate shape and length. By considering the deformity analysis, a surgical plan is established according to the surgeon's preference. This enables the design of patient-specific cutting guides and a custom-made plate (Valor Implant; Valor Implant, Barcelona, Spain), which must be 3-dimensionally printed in advance of the surgical procedure. The cutting guides facilitate precise step-cut osteotomies on the clavicle and T-shaped graft harvest on the iliac crest graft, as shown in Figure 2. This ensures accurate dimensions of the graft, optimizing the contact surfaces within the recipient site. The custom-made plate is designed to fit the patient's clavicular anatomy, providing interfragmentary fixation as well as compression forces through the plate at the clavicle-

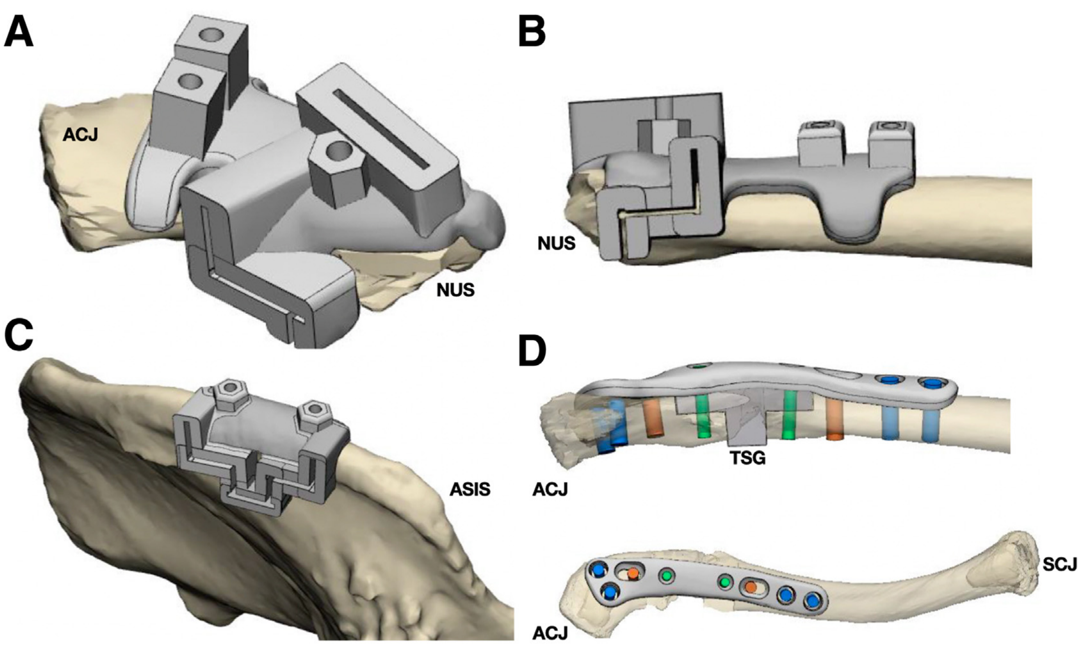

Fig 2. Three-dimensional planning and patient-specific guides. (A) Cutting guide placed lateral to the nonunion site in the clavicle. The specific holes for the 2.0-mm K-wires are visible; these serve both to fix the guide in place and to act as rails for positioning the plate and subsequent guides. The channels for the oscillating saw are also clearly observed. (B) Cutting guide placed medial to the nonunion site, with the same specifications as the medial guide. (C) Cutting guide for harvesting the T-shaped graft from the ipsilateral (right) iliac crest, prepared in the same manner as the clavicle guides. (D) Final outcome showing the customized plate and the pre-planned screw positioning. (ACJ, acromioclavicular joint; ASIS, anterior superior iliac spine; NUS, nonunion site; TSG, T-shaped graft).

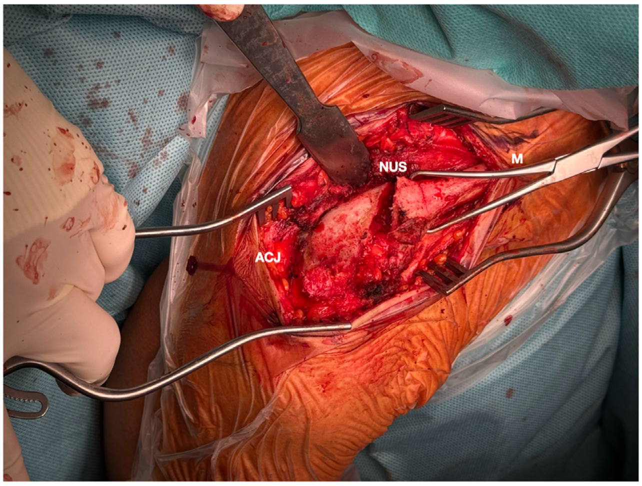

Fig 3. Right shoulder. Exposure of the nonunion site (NUS) before placing the cutting guides for the T-shaped osteotomy. (ACJ, acromioclavicular joint; M, medial.)

graft interface (Fig 2). The indication for this technique is the absence of bone consolidation on CT scans for at least 6 months with ongoing pain that limits range of motion for daily activities.

Operative Procedure

The stepwise operative procedure is shown in Video 1. The patient is placed in the beach-chair position, and the procedure begins by preparing the recipient site, namely the clavicle nonunion. An approximately 8-cm longitudinal incision is made directly over the clavicle nonunion, followed by a layered dissection through the platysma and deep fascia. The periosteum covering the clavicle is meticulously elevated to expose the nonunion (Fig 3). Careful excision of fibrotic tissue at the nonunion site is performed to ensure adequate adaptation of the custom guides to the bone surface. Because the nonunion site typically presents with abundant fibrous tissue, thorough debridement is essential until the true bony margins are exposed. The custom osteotomy guide is then applied to the bone surface and stabilized with two 2.0-mm K-wires (Fig 4). The first cut is made posteriorly (coronal plane) with precise depth control to avoid violating the caudal cortex. The saw blade remains inserted in the posterior slot so that, during the subsequent axial and sagittal cuts, the posterior cortex is preserved. This preservation of the posterior cortical bone maintains the anatomic length of the clavicle and improves structural stability. Finally, an oscillating saw is used through the remaining guide slots to complete the 3-plane osteotomy. The final shaping at the site results in a self-stabilizing T-shaped osteotomy with a 3 × 1-cm base and a 5 × 1-cm top designed to accommodate the autograft that will be similarly

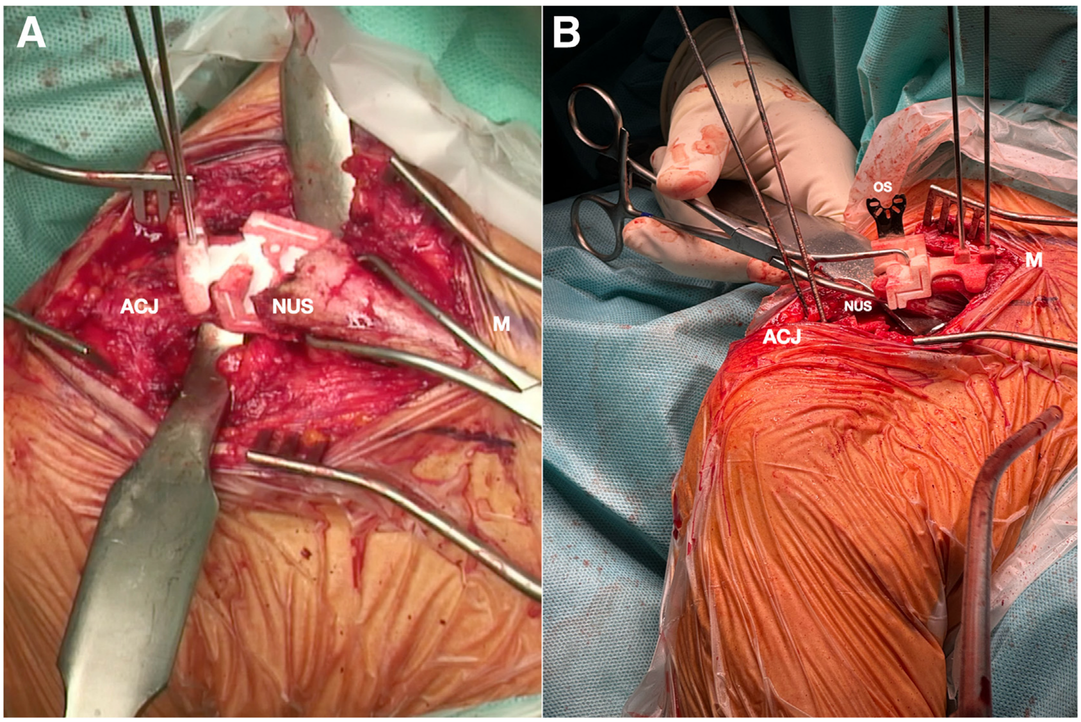

Fig 4. Right shoulder. (A) Placement of the cutting guide on the lateral clavicle fragment relative to the nonunion site. It is secured with two 2.0-mm K-wires, and the cuts are carried out through the guided channels using the oscillating saw. (B) Placement of the cutting guide on the medial clavicle fragment, following the same steps as for the lateral side. It should be noted that the lateral 2.0-mm K-wires remain in place to guide subsequent procedures. The oscillating saw (OS) is left in the coronal channel to serve as a stop for the axial cut and prevent breaching of the posterior cortex. (ACJ, acromioclavicular joint; M, medial; NUS, nonunion site.)

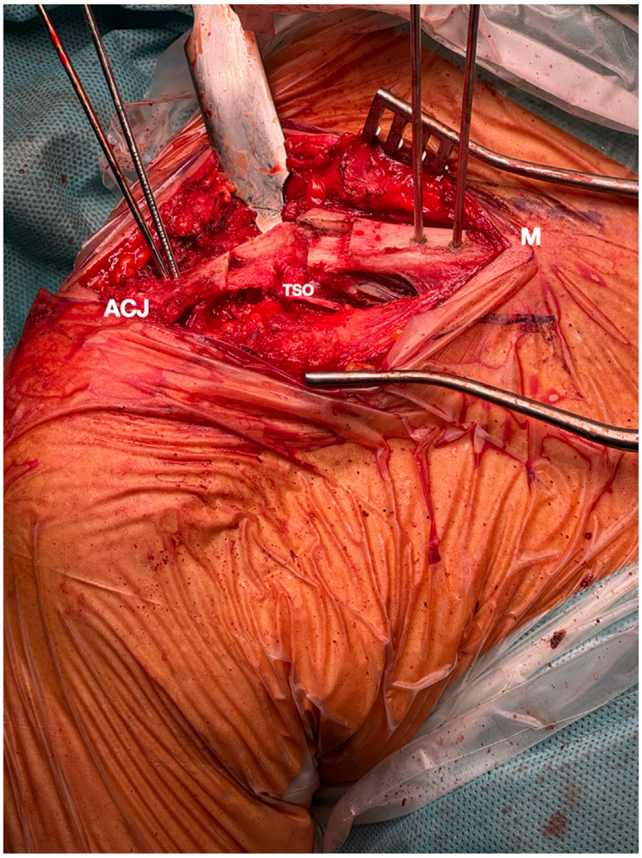

Fig 5. Right shoulder. Appearance of the T-shaped osteotomy (TSO) after removing the cutting guides. It should be noted that when the clavicle is reduced, the osteotomy is nearly self-stabilizing. The 2.0-mm K-wires remain in place to guide the plate positioning and introduce a new guide for drilling the screw holes. (ACJ, acromioclavicular joint; M, medial.)

contoured from the ipsilateral iliac crest (Fig 5). To enhance consolidation, the intramedullary canal at both ends of the clavicle is opened with a 2-mm drill.

Once both the proximal and distal clavicular fragments have been cut as planned, attention is turned to the ipsilateral iliac crest donor site. A 4-cm incision is made over the palpable iliac crest and carried down to the external oblique fascia, followed by dissection to the crest, skeletonizing the bone for optimal adaptation of the custom guide (Valor Implant). An oscillating saw is then used to harvest a tricortical T-shaped graft (3 × 1-cm base, 5 × 1-cm top) (Fig 6). Following a staged approach, the initial sagittal cut is performed, followed by the axial cut, thereby obtaining the full thickness of the iliac crest. In addition, 3 to 4 cm^3 of cancellous bone graft is obtained with a bone curette. After harvesting, the medullary canal is sealed with bone wax, and the external oblique fascia is meticulously closed over the donor site.

Returning to the recipient site, the T-shaped autograft is confirmed to fit precisely into the defect created by the custom guides, rendering the entire construct self-stabilizing (Fig 7). A custom-designed titanium locking compression plate (Valor Implant) is then positioned over the graft. The distal and proximal screw holes, which were previously used for the stabilizing 2.0-mm K-wires, are drilled and used for 3.5-mm compression screws. The plate is adapted to the bone contour and fixed using a standard compression technique. The T-shaped configuration of the graft allows it to be further stabilized to the clavicle using two 2.7-mm lag screws inserted through the plate in a superior-to-inferior direction. In this manner, the graft is compressed at the endosteal surface by the plate and along the superior surface by the fixation screws.

Under fluoroscopic control, the appropriate screws length is verified. The patient is placed in a sling for 6 weeks and transferred to the postoperative unit. A radiograph obtained at 4 months postoperatively confirms adequate plate position and bony consolidation (Fig 8).

Discussion

Clavicle nonunion is a relatively common situation leading to pain and dysfunction due to instability of the scapular waist. Surgical treatment with plate fixation and iliac crest autograft frequently leads to successful outcomes.[7,8] This article describes the surgical technique of step-cut clavicle osteotomy and T-shaped iliac crest autograft for clavicle nonunion using VSP of custom-made surgical guides and plate fixation. Table 1 describes the pearls and pitfalls that should be taken into account when performing this operation, and Table 2 lists advantages and disadvantages.

Although treatment of clavicle nonunion is controversial and isolated plating without additional bone graft has been proposed,[11] the interposition of a cortical structural allograft has traditionally been used with accelerated and high rates of healing.[9,12,13] Regardless of the use of bone graft, the technique requires the meticulous anatomic reconstruction of the initial fracture and stable fixation to maximize the chances of healing.

VSP can facilitate reconstruction of these defects with virtual manipulation of injured sites prior to surgery. Additionally, it can allow the creation of a mirror image of the uninjured side for planning purposes. This technology has previously been used successfully for different orthopaedic surgical procedures and in other bony reconstruction fields.[14-16] Moreover, 3-dimensional preoperative planning and patient-specific guides for corrective osteotomies of clavicle malunion have previously been proposed.[17-19]

In previous studies, the clavicle plate used was a standard implant that required manual contouring either intraoperatively or preoperatively.[18] In the

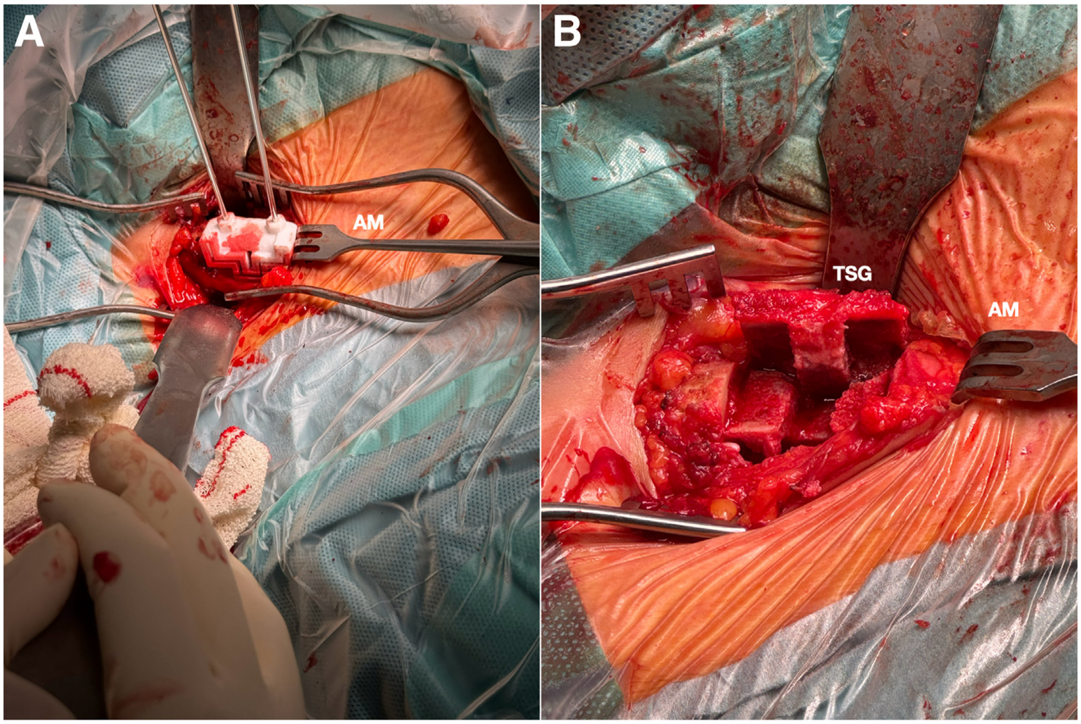

Fig 6. Right iliac crest. (A) Placement of the guide on the iliac crest in the same manner as the clavicle, secured with 2.0-mm K-wires. Note the channels to perform the guided cuts with the oscillating saw. (B) Final view of the harvested T-shaped graft (TSG) from the iliac crest. (AM, anteromedial.)

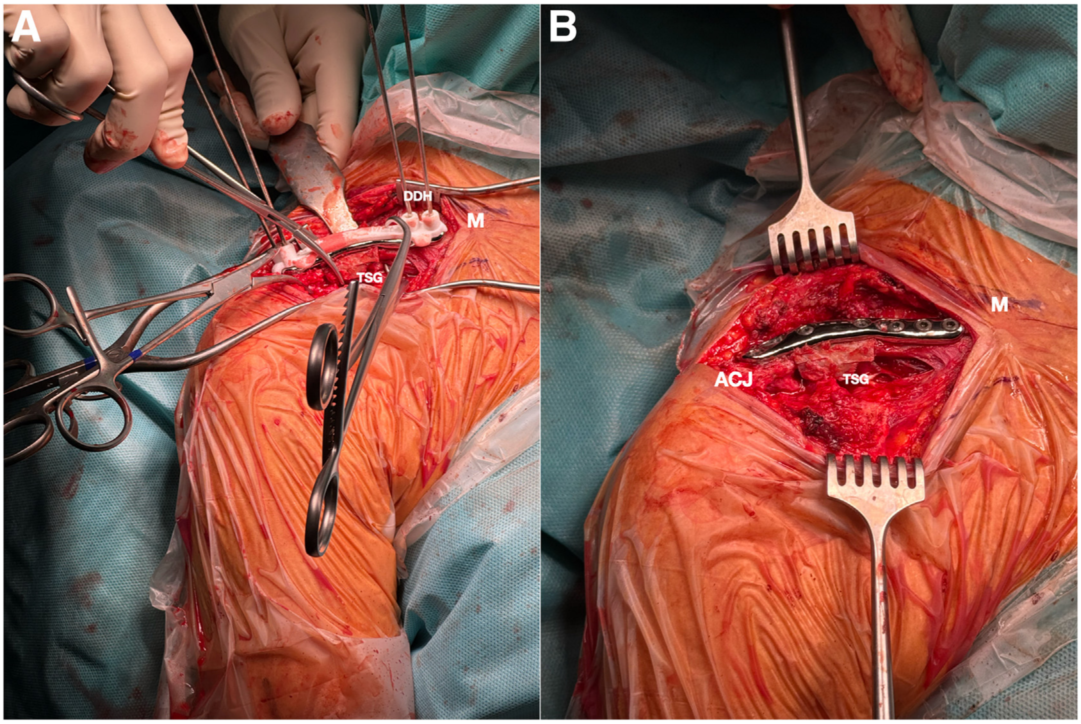

Fig 7. Right shoulder. (A) Placement of the T-shaped graft into the osteotomy region. The custom plate is applied over both the graft and the superior surface of the clavicle, followed by the placement of the drilling guide for the eccentrically oriented screws. It should be noted that both the plate and the guide fit perfectly along the 2.0-mm K-wires that have been retained from the initial guided osteotomy. (B) Final construct with the locking plate and the T-shaped graft secured by specifically planned screws. (ACJ, acromioclavicular joint; DDH, designed drilling holes; M, medial; TSG, T-shaped graft.)

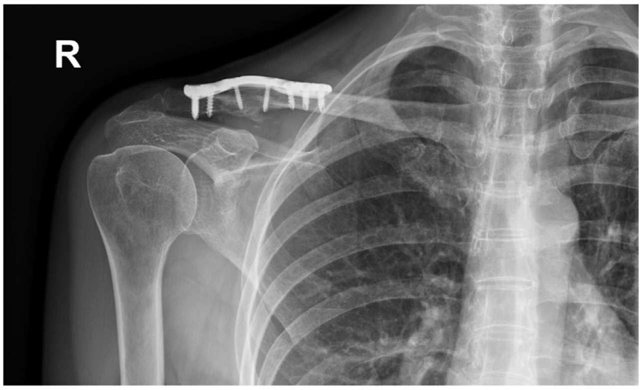

Fig 8. Final appearance of right shoulder at 4 months postoperatively. Progressive consolidation of the nonunion site is evident, with integration of the T-shaped graft. It should be noted that the screws have precisely the required length, as had been preoperatively planned. (R, right.)

present case, the contralateral clavicle was used as a template to reconstruct the patient's nonunited clavicle. VSP was used to create 3-dimensionally printed surgical guides, which facilitated step-cut osteotomy on both clavicle fragments. VSP was additionally implemented to prefabricate a patient-specific clavicle reconstruction plate, ensuring precise anatomic alignment of the clavicular segments and the T-shaped graft. The entire guided process contributes to reducing the total operative time and minimizing errors.

A further distinction from prior reports is the grafting technique. A T-shaped graft has been previously described in clavicle reconstruction to enhance bone healing by increasing surface area and providing greater stability.[10] Whereas previous studies used manually harvested corticocancellous autografts, our approach incorporates 3-dimensionally printed surgical guides to obtain a T-shaped corticocancellous autograft. Furthermore, this construct enables the stabilization of the graft to the clavicle using pre-planned 2.7-mm screws through the plate, securing the graft in place. These advancements allow for more precise integration of the clavicle, graft, and plate, thereby enhancing the predictability of the reconstruction.

There are some disadvantages of this technique related to graft donor-site morbidity and the esthetic concerns of plate fixation. VSP also has inherent drawbacks, such as increased cost of the surgical procedure. Additionally, VSP is not always feasible for urgent cases because the process of virtual planning and manufacturing custom plates can take up to 14 days. Moreover, VSP involves multiple steps, including data acquisition, coordination with a software engineer, and fabrication of patient-specific hardware.

In conclusion, the surgical technique of step-cut clavicle osteotomy and T-shaped iliac crest graft is an effective option to treat clavicle nonunion owing to inherent stability of the construct and enhanced consolidation surface. The use of patient-specific cutting guides and a custom-made plate facilitates precise clavicle osteotomies and T-shaped graft harvest on the iliac crest graft, ensuring an accurate fit of the construct and reducing the operating time.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT to improve the readability and language of the work. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Disclosures

All authors (A.A-M., A.A-M.) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 1. Pearls and Pitfalls

Pearls	Pitfalls
Meticulous dissection	When addressing pseudarthrosis, the surgeon must ensure careful dissection to avoid injury to the underlying neurovascular structures, particularly the brachial plexus and subclavian artery.
Precise nonunion site preparation	Thorough debridement of fibrous tissue at the pseudarthrosis site is essential to ensure that the proximal and distal custom-made cutting guides fit precisely to the bony contour of the clavicle.
Engineering plan oversight	It is crucial to carefully review the engineer's preoperative planning to ensure proper application of osteosynthesis principles, as well as guide the procedure according to the surrounding anatomy.

Table 2. Advantages and Disadvantages

Advantages	
	Improved anatomic fit by ensuring precise alignment of proximal and distal clavicular segments
	Enhanced graft integration through 3-dimensionally printed guides, increasing stability and bone healing predictability
	Optimized screw positioning with 3-dimensionally planned fixation, improving construct stability and reliability
Disadvantages	
	Increased cost owing to advanced imaging, virtual planning, and custom hardware fabrication
	Longer preoperative process as custom plate manufacturing can delay surgery up to 14 days
	Limited emergency applicability because VSP requires multiple steps, making use in urgent cases impractical

VSP, virtual surgical planning.

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