

Accurate Bone Tunnel Location Based on Three-Dimensional Printing Navigation Module Technology in Coracoclavicular Ligament Reconstruction: Virtual Model vs. Real Model

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Research article

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Abstract

Background: Finding ideal bone tunnel location is key to reconstruction of the coracoclavicular (CC) ligament, which has become a fundamental surgical method for acromioclavicular (AC) joint dislocation. The study aims to explore virtual model vs. real model of accurate bone tunnel location in coracoclavicular (CC) ligament reconstruction based on 3-dimensional (3D) navigation module printing technology.

Methods: Eighty human shoulders including clavicle and scapula were scanned by dual-source computed tomography (CT). CT scans of shoulder joints including clavicle and scapula were imported, the acromioclavicular joints were repositioned to form a whole model, and find the best bone tunnel through digital optimization design by Mimics 19.0 software. In Geomagic Studio software, forming the clavicle navigation module, which was generated for 3D printing. Then 10 parameters of a real bone tunnel and virtual bone tunnel can be measured and compared.

Results: Eighty human shoulders including clavicle and scapula were designed and printed successfully. Then 10 parameters of the real and virtual bone tunnels were recorded and compared. No difference was significantly found between the real and virtual bone tunnels in 10 measurements ($p>0.05$).

Conclusions: The accuracy of bone tunnel location for CC reconstruction in adult shoulders based on 3D printing navigation module technology is reliable.

Background

Acromioclavicular (AC) joint dislocation, at the cause of approximately 9% [1], is a common shoulder girdle injury. Fixation of the AC joint and reconstruction of the coracoclavicular (CC) ligament have become extremely fundamental surgical methods [2, 3, 4]. For one thing, AC joint fixation techniques contain the use of screws, hook plates and wires, which can easily lead to fracture, osteolysis and hardware related complications [2, 3]. For another, reconstruction of the CC ligament, such as the Weaver-Dunn technique, may be much weaker and more compliant than the native one with high failure rate. However, in 2007, double endobutton technique was first used for the treatment of complete AC joint dislocations [5]. Since then, with the application of the double endobutton technique, postoperative complications have been significantly improved [6, 7]. Although the use of double endobutton plate technique for the treatment of Rockwood III-VI dislocations has been widely recognized, the improvement of the double endobutton technique has never stopped [8, 9, 10].

By faithfully restoring these insertion points on the clavicle and dominating the movement of the graft on the coracoid process, the 3-tunnel reconstruction technique was closer to restoring the natural movement of the shoulder than the CC sling technique [11]. According to some recent clinical studies, the complication rate of CC reconstruction was 23% - 80% [12, 13, 14], and as one of the iatrogenic complications, coracoid fracture was more caused from drilling in the coracoid. Meanwhile, there were relatively few studies attempting to determine the ideal tunnel location [13]. However, for the repair of AC

joint dislocation, image-free navigated CC drilling had higher first-pass accuracy than conventional drill, which may help find a precise anatomic position of the bone tunnel [15]. Centered tunnels provided more strength than eccentric tunnels in the distal coracoid, and reduced the risk of coracoid process fracture [16]. Therefore, during formation of a coracoid bone tunnel, the appropriate trajectory of the drill and the central position were helpful for reducing the risk of repair failure and coracoid process fracture [17].

The purpose of this study was to make the individualized navigation module for reconstruction of CC ligament tunnel, which was used for reconstruction of AC joint, and compared with virtual model in Mimics software to analyze whether there were the differences between a real bone tunnel and a virtual bone tunnel for a novel double endobutton in AC joint reconstruction. Moreover, the study provided theoretical support and experimental basis for the popularization and application of this novel double endobutton in clinical practice. Meanwhile, demonstrating the feasibility, safety and accuracy of the navigation module is conducive to the formulation of personalized and optimized surgical preoperative planning.

Methods

Patients

The scapular thin-slice CT data of 80 patients, were retrospectively collected from the imaging department of the Affiliated Traditional Chinese Medicine Hospital of Southwest Medical University and ethical protocols were approved (KY2018032). Clavicle and scapula fractures or developmental deformities were excluded. The gender of patients was unknown.

The Design Process of 3D Printing Navigation Module

CT scans of shoulder joints including clavicle and scapula were imported, and the acromioclavicular joints were repositioned by Mimics 19.0 software to form a whole model. Then, select the point 3 cm away from the midpoint of acromioclavicular joints, and at the same time at the midpoint of the anterior and posterior clavicular in Mimics 19.0 software, which were established as the center of the circles for two cylinders: Cylinder 1 and Cylinder 2 (Radius, 1.5 mm and 3.0 mm, respectively). Meanwhile, adjust the center of the lower cylinder through the middle point of the coracoid process root and medial and lateral margins, ensure that the upper surface of Cylinder 2 exceeded the clavicle plane by about 2 cm (the tunnel length of the future navigation module). Next, Open Geomagic Studio and shear the surface around the bone tunnel on the upper surface of the distal clavicle. Select the plane after the shearing and click on "shell extraction"(the thickness, 2.5mm, and the direction, upward). We called it the clavicle navigation board, which was imported into Mimics 19.0, and uniting "clavicle navigation board" and "Cylinder 2" can generate the reconstruction model of the clavicle navigation module (Fig. 1).

Far away from the coracoid-clavicle tunnel and acromioclavicular joint, three new Cylinder linking rods were constructed to link the clavicle and scapula, and the clavicle-scapula model can be generated. Then

10 parameters of virtual bone tunnel can be measured recorded with an accuracy of up to 0.1 mm (Fig. 2):

1. AB: the distance of clavicular tunnel: the distance between point A and point B (point A supraclavicular plane needle point, point B subclavian plane needle point);
2. CD: the distance of coracoid tunnel: the distance between point C and point D (point C upper plane of coracoid process needle point, point D subcoracoid plane needle point);
3. BC: the distance between B and C;
4. AD: the distance between A and D;
5. EF: the distance between E and F (point E clavicular needle point, point F anterior clavicular margin);
6. EG: the distance between E and G (point G posterior clavicular margin);
7. EH: the distance between E and H (point H middle point of acromioclavicular joint);
8. OP: the distance between O and P (point O the point of coracoid process needling, point P the inner margin of coracoid process);
9. OS: the distance between O and S (point S the outer margin of coracoid process);
10. OQ: the distance between O and Q (point Q the point of coracoid process needling).

3D Printing and Establishment of Real Bone Tunnel

The data of clavicle navigation module and clavicle scapula module were transformed into print file of Replicator Z18 printer by MakerBot Print software (printing parameters: print mode, balance; layer height, 0.2 mm; wall thickness, 2 times the thickness of sprinkler head; sprinkler moving speed, 150 mm/s; sprinkler temperature, 215 C; sprinkler wire diameter, 1.77 mm; the platform withdrawal height, 0.5 mm; the top thickness, 0.804 mm; the bottom thickness, 0.8 mm; the minimum supporting angle, 68 degrees; the supporting density, 16%; and the printing material: biodegradable plastic polylactic acid (PLA)). MakerBot Replicator Z18 3D printer was used for producing individual specimen entity (Fig. 3). The relevant supporting structures around the module were removed and the rough edges were trimmed after printing. The clavicular navigation module function adhered to the supraclavicular plane of the clavicular scapula model tightly. According to the tunnel direction of the clavicular navigation module, a Kirschner wire with a diameter of 2.0 mm was inserted. Then 10 parameters of the actual navigation tunnel were measured. To avoid intra-observer and inter-observer variation, an investigator, who had >2 years of experience in 3D printing work, measured and recorded each parameter carefully only once.

Statistical analyses

All data were analyzed by SPSS, version 20.0 (IBM Corp., Armonk, NY, USA). The results were presented as mean and standard deviation. Then, Ryan-Joiner test was used for analyzing the normality of the continuous data distribution. Paired t-tests could be adopted if the data were normally distributed, to assess whether there were differences between the actual navigation tunnel and the virtual bone tunnel, or signed-rank test was applied. In addition, P value was higher than 0.05 as statistically no significant.

Results

Eighty human shoulders were designed and printed successfully. Then 10 parameters of the real and virtual bone tunnels were measured and compared in Figure 2. All data were normally distributed, and relative data were recorded as a form of mean \pm standard deviation (Table 1).

No significant difference were found between the real bone tunnels and virtual bone tunnels in 10 measurements (AB 11.37 ± 0.29 mm in the real bone tunnels vs. 11.43 ± 0.28 mm in the virtual bone tunnels, $p=0.249$; CD 12.76 ± 0.41 mm in the real bone tunnels vs. 12.56 ± 0.37 mm in the virtual bone tunnels, $p=0.226$; BC 7.69 ± 0.72 mm in the real bone tunnels vs. 7.81 ± 0.74 mm in the virtual bone tunnels, $p=0.131$; AD 24.28 ± 0.52 mm in the real bone tunnels vs. 24.10 ± 0.47 mm in the virtual bone tunnels, $p=0.235$; EF 8.91 ± 0.29 mm in the real bone tunnels vs. 8.79 ± 0.26 mm in the virtual bone tunnels, $p=0.247$; EG 7.79 ± 0.32 mm in the real bone tunnels vs. 7.81 ± 0.34 mm in the virtual bone tunnels, $p=0.179$; EH 34.13 ± 0.48 mm in the real bone tunnels vs. 34.41 ± 0.31 mm in the virtual bone tunnels, $p=0.194$; OP 7.13 ± 0.24 mm in the real bone tunnels vs. 7.23 ± 0.23 mm in the virtual bone tunnels, $p=0.188$; OS 6.64 ± 0.20 mm in the real bone tunnels vs. 6.56 ± 0.18 mm in the virtual bone tunnels, $p=0.101$; OQ 25.67 ± 0.97 mm in the real bone tunnels vs. 25.39 ± 0.99 mm in the virtual bone tunnels, $p=0.344$) (Table 1).

Table 1 The measurements of the real bone tunnels and virtual bone tunnels

	the real bone tunnels	the virtual bone tunnels
AB (mm)	$11.37\pm 1.30^*$	11.43 ± 1.24
CD (mm)	12.76 ± 1.82	12.56 ± 1.63
BC (mm)	$7.69\pm 3.22^*$	7.81 ± 3.29
AD (mm)	$31.97\pm 4.05^*$	31.91 ± 3.86
EF (mm)	$8.91\pm 1.29^*$	8.79 ± 1.18
EG (mm)	$7.79\pm 1.45^*$	7.81 ± 1.40
EH (mm)	$34.13\pm 2.17^*$	34.41 ± 1.40
OP (mm)	$7.13\pm 1.08^*$	7.23 ± 1.02
OS (mm)	$6.64\pm 0.89^*$	6.56 ± 0.82
OQ (mm)	$25.67\pm 4.34^*$	25.39 ± 4.45

Discussion

clavicle [18]. As a common shoulder injury, AC dislocation accounted for about 9% [1]. When acromion was in the statement of an adducted shoulder, the mechanism of AC joint injury was usually a direct impact, which produced a series of injury: AC ligament failure, then failure of the CC ligaments, even the muscular attachments of the trapezius and deltoid in the clavicle [2]. AC dislocation could not only cause AC joint pain and inconvenient movement, but also impair the quality of the patient's normal life or work.

Fixation of the AC joint and reconstruction of the coracoclavicular (CC) ligament have become extremely fundamental surgical methods [2, 3, 4]. Anatomic CC ligament reconstruction could help restore arm function by rectification of the deformity for the acquisition of static and dynamic stability [19]. In CC reconstruction method, the Modified Weaver-Dunn technique was the most widely adopted [20]. But postsurgical complications contained sustainable weakness, pain, and clavicular osteolysis [18]. The Weaver-Dunn technique, may be much weaker and more compliant than the native one with high failure rate [21]. Screws, hook plates and wires, which were usually as AC joint fixation techniques, can easily lead to fracture, osteolysis and related complications [2, 3].

In 2007, for the treatment of complete AC joint dislocations, double endobutton technique was first used and proved effective [5]. Since then, with the application of the double endobutton technique, postoperative complications have been significantly improved [6, 7]. In the AC joint, the double endobutton technique could display stronger load to-failure characteristics and yield less translation than the cerclage sling reconstruction, which was better to restore native AC–CC biomechanics for reducing post-operative pain and preventing recurrent subluxation and dislocation than an allogenic graft [7]. The proposed mini-open technique using the double-button fixation system could be recommend for all type IV injuries and type III injuries in heavy manual labors and high demand upper extremity players [6]. Arthroscopy-assisted reconstruction of the CC ligament by endobutton fixation proved a safe and easy way for the treatment of AC joint dislocation, which can provide reliable fixation, a fast recovery and cause less trauma [8]. The continuous loop device can eliminate the possibility of knot breakage or slippage, and MRI suggested a robust healing response, which can be recommended both for chronic and acute dislocations [9]. Although the use of double endobutton plate technique for the treatment of Rockwood III-VI dislocations has been widely recognized, the improvement of the double endobutton technique has never stopped [8, 9, 10]. According to reset requirement during operation, our novel double endobutton can adjust loop length for satisfying different individual operative methods.

With this limited exposure of the coracoid and minimally invasive approach, a surgeon can place the suture anchors by using the bone tunnel to maintain AC joint well [22]. The 3-tunnel reconstruction technique faithfully restored these insertion points on the clavicle and dominated the movement of the graft on the coracoid process, which was closer to restoring the natural movement of the shoulder than the CC sling technique [11]. Furthermore, for the treatment of AC dislocation, the CC reconstruction using either tendon grafts or cortical fixation buttons produced an overall complication rate of 27.1% [12]. The anatomic CC reconstruction were related with complications such as coracoid and clavicle fractures, and

coracoid fracture was more caused from drilling in the coracoid [13]. It was crucial to place the coracoid button centrally under the coracoid base for preventing failure, which also suggested how vital to determine the ideal tunnel location [3, 8, 13-14].

By using 3D navigation, the accuracy of AC joint reconstruction could be improved [23], and image-free navigated CC may help find a precise anatomic position of the bone tunnel drilling with higher first-pass accuracy than conventional drill [15]. Meanwhile, compared to conventional operation, three-dimensional (3D) printing technology had more advantages on the operative time and intraoperative blood loss [24]. The study adapted the centered tunnels in the distal coracoid, which provided more strength for reducing the risk of coracoid process fracture. And make the individualized 3D navigation module for reconstruction of CC ligament tunnel, which can improve the accuracy of bone tunnel location and decrease the risk of the complications. Then 3D print navigation module, which compared with virtual model in Mimics software. The outcome suggested that no differences existed between a real bone tunnel and a virtual bone tunnel for a novel double endobutton in AC joint reconstruction. The accuracy of bone tunnel location for CC reconstruction in adult shoulders based on 3D printing navigation module technology was reliable.

The present study had some limitations. First, in this study, the samples were restricted to the western part of China and gender were unknown. The inferences about the 3D printing navigation module were also limited, especially referring to the treatment of AC joint dislocation. A professional researcher only measured all the samples once carefully, and some observational errors could not be avoided. Finally, this study was an experimental research not a clinical trial, so no sufficient clinical data to prove that the accuracy of bone tunnel location for CC reconstruction in adult shoulders based on 3D printing navigation module technology was reliable and reduced the risk of related complications.

Conclusion

The individualized 3D navigation module for reconstruction of CC ligament tunnel, can improve the accuracy of bone tunnel location and decrease the risk of the complications. The research outcome suggested that there were no differences between the real bone tunnels and virtual bone tunnels for a novel double endobutton in AC joint reconstruction. The accuracy of bone tunnel location for CC reconstruction in adult shoulders based on 3D printing navigation module technology was reliable.

Abbreviations

CC: coracoclavicular; 3D: 3-dimensional; CT: computed tomography; AC: Acromioclavicular

Declarations

Ethics approval and consent to participate

Ethical protocols were approved prior to conducting the study by Affiliated Traditional Chinese Medicine Hospital of Southwest Medical University (KY2018032). All patient signed a General Consent of the Ethical Committee of Affiliated Traditional Chinese Medicine Hospital of Southwest Medical University for using and publishing their data for scientific use.

Availability of data and materials

Data are available from Lei Zhang(e-mail: zhanglei870722@126.com) for researchers who meet the criteria for access to confidential data.

Competing interests

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication.

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Authors' contributions

Lei Zhang: Conception and design; Qi Feng and Lu-jing Xiong: Edit and process articles; Si-yuan He: Data collection and picture data processing; Gang Yi and Xiao-guang Guo: literature search and picture data processing, Xin Zhou: literature search.

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Figures

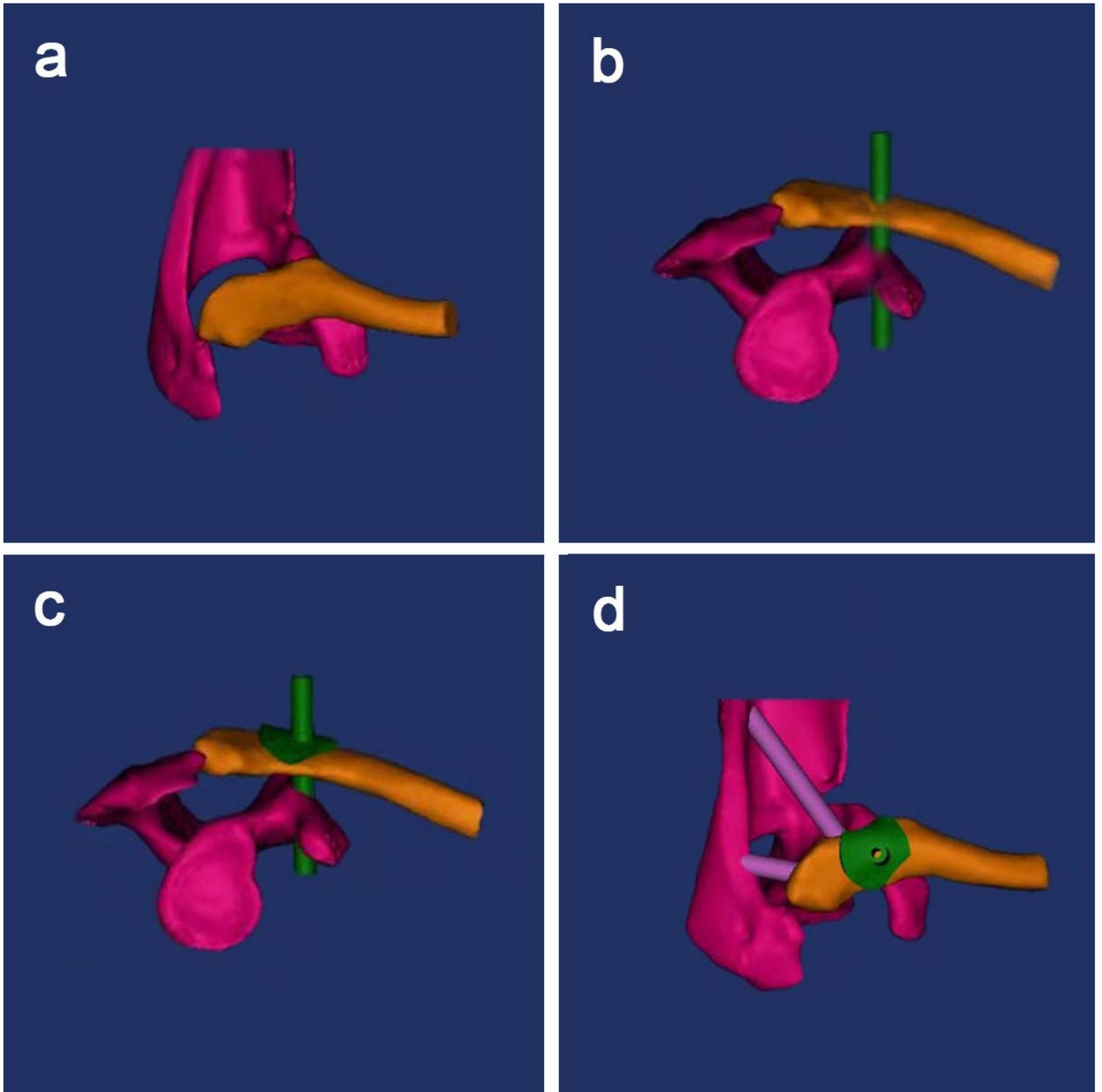


Figure 1

Establishment process of navigation module (a) Scapula and clavicle model; (b) scapula and clavicle model with cylinder; (c) scapula and clavicle model with navigation module; (d) reconstruction model with navigation module of clavicle.

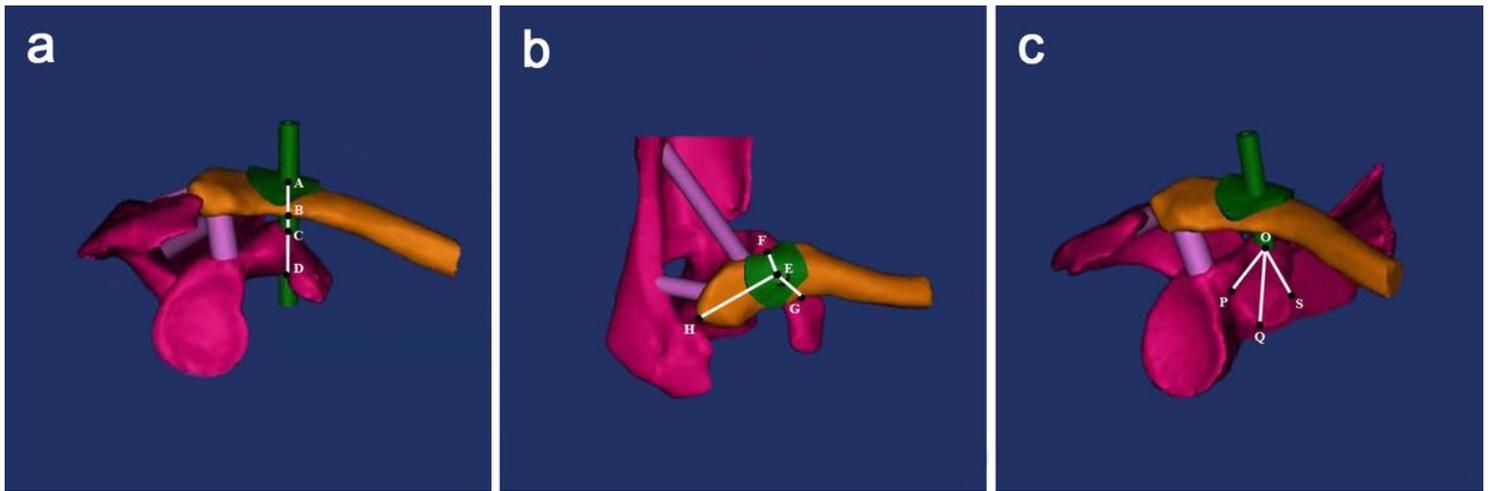


Figure 2

Ten measurements of virtual bone tunnel (a): Measurements of the length of the clavicle tunnel (AB), the length from the lower plane of the clavicle to the upper plane of the coracoid (BC), the length from the upper plane of the clavicle to the lower plane of the coracoid (AD), and the length of the coracoid tunnel (CD); (b): Measurements of the length between the point of the clavicle needle point and the front edge of the clavicle (EF), the length between the needle point of clavicle and the posterior edge of clavicle (EG), and the length between the point of the clavicle needle point and middle point of acromioclavicular joint (EH); (c): Measurements of the length between the point of coracoid process needling and the inner margin of coracoid process (OP), the length between the point of coracoid process needling and the point of coracoid process needling (OQ), and the length between the point of coracoid process needling and the outer margin of coracoid process (OS).

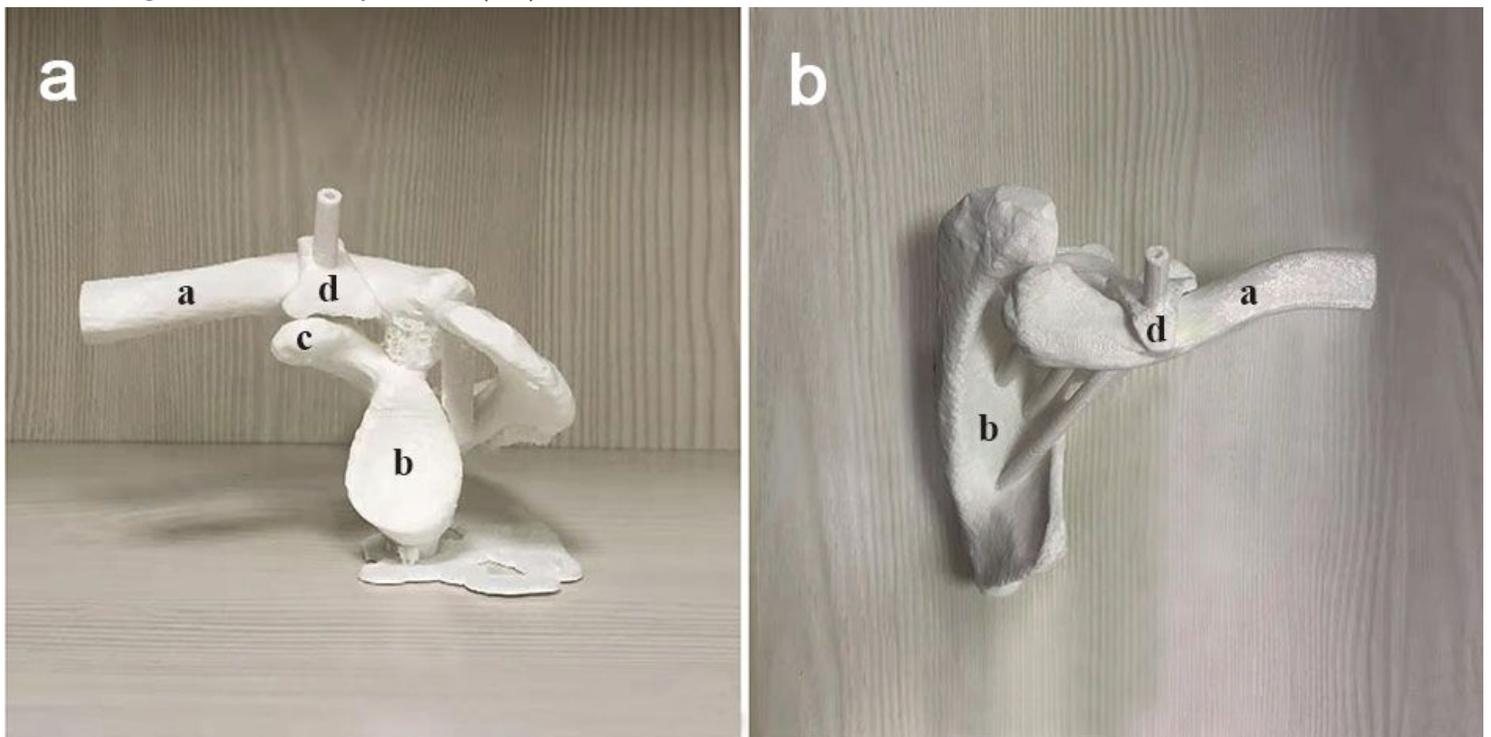


Figure 3

Printed specimen entity (a) Front view: a stands for clavicle; b stands for Scapula; c stands for Coronoid process; d stands for navigation module; (b) Top view.