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Research Article

Comparison of two methods for coracoclavicular ligament reconstruction: A finite element analysis

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ABSTRACT

Objective: This study aimed to compare two different tendon grafting techniques for coracoclavicular ligament reconstruction from the data obtained using finite element analysis.

Methods: Three different finite element models of the shoulder girdle were formulated using computerized tomography images: the reference model, coracoid loop technique (CLT), and drilling technique (DT) model. In all these models, forces were applied to the clavicle along three axes (x, y, and z) of the trapezius and sternocleidomastoid muscles. Thereafter, data regarding the loading values of the tendon grafts, loads on the coracoid base, and coracoclavicular vertical distance were measured.

Results: While the reference model yielded the lowest values for all the loading conditions as well as the shortest coracoclavicular distance, the DT model demonstrated the highest values for all the loading conditions and the largest coracoclavicular distance.

Conclusion: Different tendon grafting techniques may offer different loading values on both bone surface and tendon graft during coracoclavicular ligament reconstruction. The drilling technique may be associated with increased loading on the tendon graft and bone surface, causing further loss of reduction and consequent complications.

Introduction

Acromioclavicular joint separation is a common injury among young active population as a result of their involvement in the contact sports, and it accounts for approximately 9% of all shoulder girdle injuries (1-3). They are classified as the Rockwood classification. While low-grade separations (Rockwood type 1-2) are treated non-operatively, high-grade dislocations (Rockwood type 4-6) with complete rupture of the coracoclavicular ligaments which are rarely seen require surgical treatment. There is evidence to suggest that the treatment of Rockwood type III is less clear and controversial (4). The purpose of surgery is to reconstruct anatomy, relieve pain, improve strength and early mobilization of joint (5).

Different surgical strategies have been described for high-grade acromioclavicular joint separation, which involve rigid (screws or hook plates) or nonrigid (autograft, allograft, or synthetic implants) techniques (6, 7). Anatomic coracoclavicular ligament reconstruction has become popular with fruitful patient outcomes (8). Coracoclavicular ligaments reconstruction with tendon graft is the most commonly used anatomical surgical treatment of high-grade acromioclavicular separation.

In the anatomical coracoclavicular ligament reconstruction, the tendon graft can be performed with three different coracoid fixation techniques. In the first technique, the tendon graft is looped bypassing beneath the coracoid base. In the second technique, the tendon graft is passed beneath the coracoid base and fixed without crossing. In the third technique, the graft is passed through the hole drilled into the coracoid base and the graft is fixed without crossing. While there are few comparative studies on the first and third

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techniques, we have found no comparative inquiries on the second technique after a systematic review of the literature. All three methods may result in complications such as loss of reduction, coronoid fractures, and distal clavicle fractures (7, 9, 10).

The CLT and the DT are best known graft techniques. Following a systematic analysis of the previous research, it can be noted that there are few studies comparing these two tendon graft methods although we can find several studies evaluating the CLT and DT separately (11). To the best of our knowledge, there is no study evaluating the effects of loading on tendon and bone surfaces in terms of tendon graft techniques in coracoclavicular ligaments reconstruction. In this regard, the purpose of this study was to determine which technique is better, by investigating the effects of loading on tendon graft and bone surfaces in coracoclavicular ligaments reconstruction with finite element analysis.

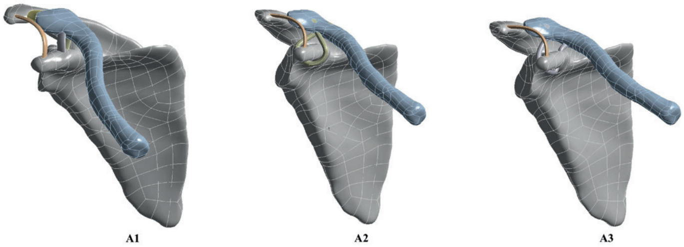

Figure 1. Created models. A1: reference model; A2: CLT model; A3: DT model

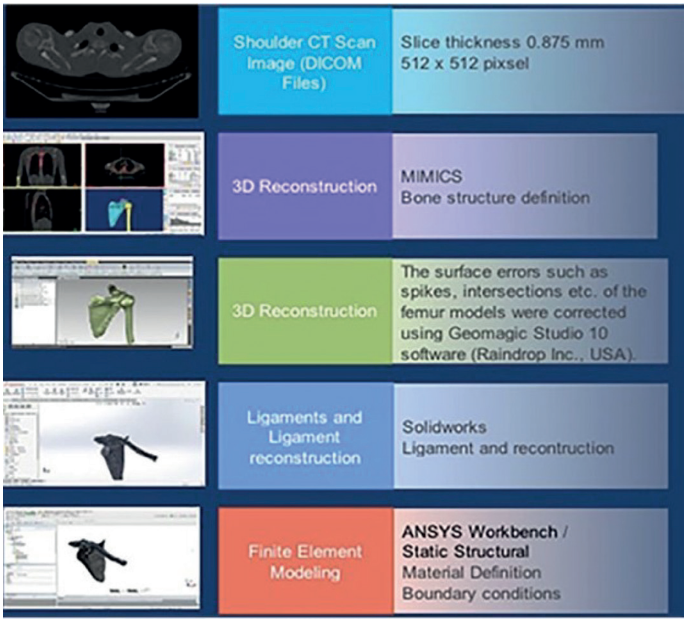

Figure 2. Process of 3D modeling and analysis

Materials and Methods

Creating and analyzing models

A 30-year-old male patient's right shoulder joint was modeled using three-dimensional computerized tomography (CT). The CT images were obtained by scanning at 120 kV at a pixel size of 0.891 mm and resolution of 512×512 pixels. The images were recorded in the Digital Imaging and Communications in Medicine format. Materialise Mimics® (Materialise Interactive Medical Image Control System, Materialise NV, Belgium), an interactive software for the visualization and segmentation of CT images, was used.

The Geomagic® Studio (Raindrop Geomagic, Inc.) program was used to reverse the unwanted geometry on the resulting shoulder model. The images were converted into the Initial Graphics Exchange Specification format and sent to SolidWorks® (Dassault Systèmes SolidWorks Corp., USA) for creating links on the resulting modified models. The reference model was formed by modeling the acromioclavicular joint and coracoclavicular ligament using the SolidWorks® program.

In the CLT model, the tendon graft passed beneath the coracoid base by the hanging method and by crossing before fixing the clavicular bone tunnels. In the DT model, we drilled one tunnel in the center–center of the coracoid surface and the tendon the tendon was fixed to clavicular bone tunnels, by being passed through the coracoid tunnel without crossing (12).

The clavicular bone tunnels were taken from the same location for both these models. We used the tunnel ratio described in the literature to determine the two tunnel locations of the clavicle. The tunnel ratio defines the distance from the lateral border of the clavicle to the center of each bone tunnel divided by the total length of the clavicle (6, 7). The tunnel locations for all the models were determined according to these values: 0.25 for conoid tunnels and 0.16 for trapezoid tunnels (13). The CLT, DT, and reference models are indicated in Figure 1.

The flowchart of the modeling is shown in Figure 2. The resulting models were inputted to the ANSYS Workbench (version 18, ANSYS Inc., Canonsburg, PA) program for finite element analysis.

Mesh and material properties

ANSYS Workbench software was used to construct the tetrahedral mesh network for the bone structures. The network size for the bone structures was 2 mm. The network size for the ligaments was 0.5 mm. On average, our models comprised 299810 nodes and 149167 elements. Solid187 was used as the element type. The analysis was performed nonlinearly according to the Newton-Raphson method.

For this analysis, the mechanical behaviors of the cortical–cancellous bone structures and ligaments were taken as isotropic, elastic, and homogeneous, as per the studies in the literature. Young's modulus and Poisson's ratio are defined (Table 1) (14, 15).

Boundary and loading conditions

After introducing the material properties, tendon grafts used in the CLT and DT models were defined as frictionless contacts. In addition, the sternal joint surface and acromion bottom surface of the clavicle were fixed (16). In this analysis, the forces exerted on the clavicle by the three axes (x, y, and z) of the trapezius and sternocleidomastoid muscles were described and noted (Table 2) (Figure 3) (17).

For all the models, we calculated the coracoclavicular vertical distance-taken from the same point-between the uppermost border of the coracoid process and inferior clavicular surface (Figure 4).

Results

When we applied the muscle forces to the clavicle, the highest value on the tendon graft was calculated in the DT model (2.6359 MPa). The lowest loading values were calculated in the trapezoid (0.6823 MPa) and conoid (0.7819 MPa) for the anatomical reference model. The loading value in the CLT model was 1.7205 MPa.

Table 1. Material properties of the models

	Young's Modulus (MPa)	Poison Rate
Cortical Bones	17000	0.3
Cancellous Bones	1000	0.3
Ligaments	9.6	0.3

Table 2. Applied muscle forces

	Muscle Force Components (Newton, N)		
Muscles	**Fx**	**Fy**	**Fz**
Trapezius	2.8 N	22.4 N	- 30.5 N
Sternocleidomastoid	- 1.5 N,	14.2 N	- 4.2 N

With respect to the coracoid base and distal clavicle, the highest loading values were 1.3006 and 2.1817 MPa for the DT model, the lowest loading values for the reference model were 0.0842 and 1.6359 MPa, and the loading values for the CLT model were 0.1687 and 1.8239 MPa, respectively. All the loading values are summarized in Table 3.

The coracoclavicular distance measurement was higher for the DT (13.523 mm) model than that for the CLT model (13.245 mm). In the reference model, coracoclavicular distance was measured 12.754 mm (Figure 4).

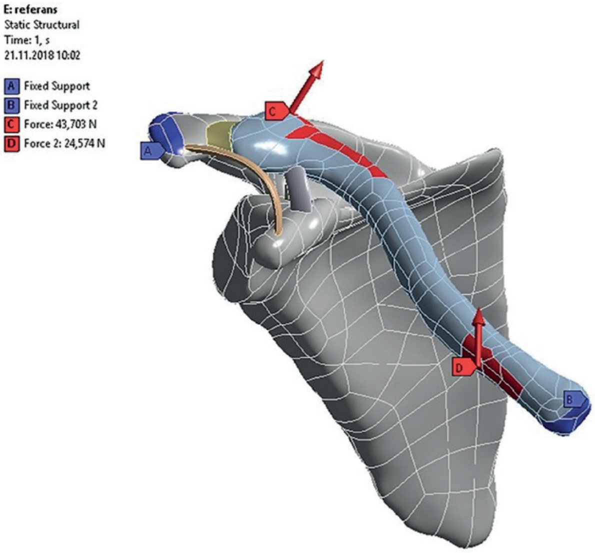

Figure 3. Boundary and loading conditions. A, B: fixation area; C, D: applied muscle forces

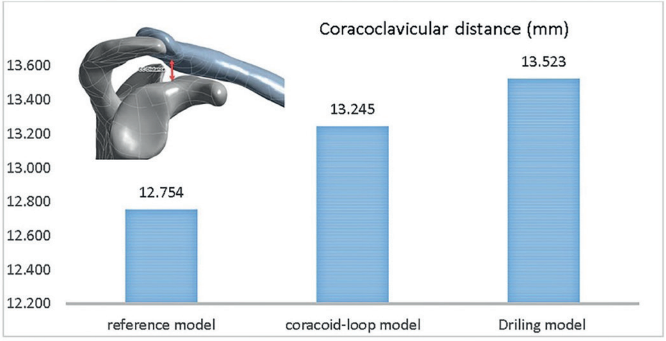

Figure 4. Coracoclavicular distance measurement values

Table 3. Maximum equivalent stress (MES) values for all the models

		MES on Tendon Graft (MPa)	MES on Coracoid Base (MPa)	MES on Distal Clavicle (MPa)
Reference Model	Conoid	0.7819	0.0842	1.6359
	Trapezoid	0.6823		
Coracoid Loop Technique Model		1.7205	0.1687	1.8239
Drilling Technique Model		2.6359	1.3006	2.1817

Discussion

Numerous methods have been described for the surgical intervention of high-grade acromioclavicular joint injuries (18-20). Nonanatomical reductions provide a weaker construct than anatomical reductions with a tendon graft (21). Utilizing tendon graft fixation anatomic techniques are more stable about maintenance of reduction and have a higher achievement (18). CLT and DT are the most popular used tendon graft techniques in anatomical coracoclavicular ligament reconstruction (9, 22). Although these procedures result in good clinical outcomes and the hope of decreasing complications, there may occur such complications as distal clavicle fractures, coracoid base fractures and reduction loss in both techniques (7-9, 23). In a systematic review and meta-analysis, the high rate of clavicular and coracoid complications was observed (9.7%), although the failure rate in tendon graft construct was 20.7% (24). The main purpose of the study was to compare the loading values and associate them with complications.

Distal clavicle fracture after tendon graft fixation has been addressed in a growing body of research, but there are a few clinical studies comparing the two ligament reconstruction techniques with different results on the risk of clavicular fracture. Considering the findings of the previous research, it can be noted that drilling the clavicle increases the risk of distal clavicle fracture. Due to tunnel drilling of clavicle in the anatomic coracolavicular ligament reconstructions, up to 18% risk of clavicle fracture in patients have been reported in the previous research (25, 26). However, it is still controversial which technique causes more clavicle fractures. In a comparative study, while the investigators found three clavicle fractures (18% within group, 11% in overall) in the CLT group, they found no clavicle fracture in the DT group (11). In the current study, clavicle fixation was performed by the same method. In this sense, the tendon graft was fixed clavicle by drilling two clavicle bone tunnels to approximate the native coracoclavicular ligaments in both techniques. Unlike the evidence in the previous research, we found that loads values on distal clavicle were higher in the DT model. This difference in result may have derived from the factors affecting the clavicle fractures in surgical practice. In other words, it is challenging to standardize surgical standardization because of the patients' specific conditions and surgical techniques such as drill diameter, tunnel location, with or without tendon graft.

A limited number of clinical trials reveals that the use of bony tunnels in the coracoid base increases the risk of coracoid fractures (27-29). Gerhardt et al. and Bindra et al. used different coracoid drilling techniques with or without tendon grafts and reported isolated coracoid fractures (30, 31). Suture button techniques without tendon grafts have a risk of fracture due to tunnel opening in the clavicle and coracoid base (1). Passing the tendon graft through the coracoid tunnel increases the risk of coracoid fractures compared with that when it is looped under the coracoid base. Milewski et al. reported two patients (20%) with coracoid fractures in the DT group, but no coracoid fracture was reported in the CLT group with tendon graft (11). In our model, we drilled one tunnel in the center-center of the coracoid base; earlier studies have suggested that the best coracoid tunnel orientation is the center–center orientation. The loading on the coracoid base was found higher in the DT model and this is a possible reason which in turn increases the risk of coracoid base fracture.

In our study, we ignored the displacement of acromioclavicular joints in the horizontal plane. Vertical plane displacement was calculated by measuring the coracoclavicular distance. When there is an increase in coracoclavicular distance, the overload on the tendon may cause a graft failure at one point and results in acromioclavicular seperation. Additionally, coracoclavicular distance measurement is used in acromioclavicular seperation classification. The greatest challenge to reconstructive procedures for acromioclavicular separation has been the loss of reduction. Coracoclavicular distance measurement after surgical treatment can also be used to ensure reduction continuity. Spencer et al. reported 47% graft failure in patient with the DT and 22% failure in patient with the CLT group (32). Milewski et al. utilized 27 cases of anatomic reconstruction: 10 cases in the DT group and 17 cases in the CLT group. In the DT group, loss of reduction was observed in 5 patient, whereas 2 loss of reduction was observed in the CLT group (11). While Zhu et al. performed anatomic reconstruction of the coracoclavicular ligament, by using an allograft with coracoid drilling method total of 18 patients, and observed loss of reduction in 10 patients (56%), Carofino and Mazzocca reported the loss of reduction only a patient in the CLT group (7, 9). We measured the coracoclavicular distance and tendon graft loads higher in the DT model. The increase in vertical distance and overload on tendon graft loads may be related with loss of reduction.

We are well aware that this study has several limitations. The main limitation of this study is the values in actual conditions and those obtained in this study may be different because finite element analysis does not provide real and continuous loading conditions. Another limitation is that only one shoulder girdle joint was considered; this may not be sufficient to standardize the obtained results. Therefore, further investigations involving biomechanical and clinical studies are needed to evaluate this topic.

In conclusion, tendon grafting techniques lead to different loading values on the bone surfaces and tendons during coracoclavicular ligament reconstructions. The DT model for the anatomical reconstruction of acromioclavicular separation is associated with increased loadings on the graft and bone surfaces, leading to further loss of reduction and complications.

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Informed Consent: N/A.

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Conflict of Interest: The authors have no conflicts of interest to declare.

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