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ORIGINAL PAPER

Evaluation of the clavicular tunnel placement on coracoclavicular ligament reconstruction for acromioclavicular dislocations: a finite element analysis

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Abstract

Purpose The two-tunnel coracoclavicular ligament reconstruction (CLR) technique is one of the treatment approaches commonly used in the surgical treatment of acromioclavicular (AC) injuries. Clavicular tunnel malposition is one of the major causes of failure in coracoclavicular ligament reconstruction. The main purpose of this study was to investigate the effects of clavicular tunnel placement on tendon loading in the CLR technique with finite element analysis.

Methods Models of clavicle and scapula were constructed using computerized tomography images. Two clavicular bone tunnel reconstruction models were created with the tendon passing through the conoid and trapezoid tunnels. Four models based on the tunnel ratio (TR) method and defined as primary, anatomic, medialized, and lateralized were constructed to evaluate the effect of tunnel placement on loading conditions during tendon graft. All models were loaded by insertion from the trapezius and sternocleidomastoid muscles. The loading on the tendon were evaluated with the finite element analysis.

Results The highest load value measured on the tendon was in the anatomic model (0.789 kPa), and the lowest load value (0.598 kPa) was measured in the lateralized tunnel model. The load value of the primary model was (0.657 kPa), and the medialized model's value was (0.752 kPa).

Conclusions In two-tunnel CLR technique, tendon loadings are related to tunnel placement. Medialized tunnel placement increases tendon loading. The TR method may be an appropriate option for determining tunnel placement.

Keywords Acromioclavicular dislocation · Coracoclavicular reconstruction · Tunnel placement · Finite element analysis · Conoid ligament · Trapezoid ligament

Introduction

Acromioclavicular (AC) joint injuries are commonly seen in young athletes engaged in contact sports such as hockey, rugby, wrestling, and soccer [1, 2]. The goal of the treatment is to restore the biomechanical functions of the AC joint by creating the physiological ligament geometry [3]. Rockwood type 1, 2, and 3 injuries are usually treated conservatively, while type 4–6 injuries and type 3 injuries in elite athletes are surgically treated [2, 4].

Recently, the two-tunnel coracoclavicular ligament reconstruction (CLR) technique is one of the most commonly used surgical options for the treatment of acute and chronically AC injuries [5, 6]. Two-tunnel CLR has gained popularity due to successful clinical outcomes and high biomechanical stability [1, 7]. Despite its popularity, the failure of two-tunnel CLR is still a major problem [7–9].

Traditionally, in the two-tunnel CLR technique, trapezoid and conoid tunnels are placed 25 and 45 mm medial to the lateral corner of the clavicle, respectively [6, 10, 11]. It is reported that tunnels should be positioned based on a "tunnel ratio" (TR) [12]. This ratio is calculated by the distance from the lateral edge of the clavicle to the center of each clavicular

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tunnel divided by the total clavicular length. Based on this method, higher survival rates were reported at a ratio of 0.20–0.25 for the conoid tunnel and a ratio of 0.13–0.16 for the trapezoid tunnel after fixation [9]. Tunnels located outside of these ratios have been associated with the failure of two-tunnel CLR [7, 9].

Nowadays, finite element analysis (FEA) is being used widely for examining glenohumeral and acromioclavicular joint pathologies [13, 14]. This method allows stress and strain distribution on soft tissues [15].

To the best of our knowledge, there is no study evaluating the effects of tunnel placement on graft loadings in two-tunnel CLR. The aim of the current study was to investigate the loading on graft in the two-tunnel CLR technique with different tunnel placements on clavicle by using FEA. Our hypothesis is that fixation performed with the medialized tunnel will cause increased loadings on the graft.

Materials and methods

Creating bone models

Data from the "Visible Human Project" study were used to construct the three-dimensional clavicle and scapular bone models [16]. Three-dimensional (3D) bone models were created using 3D-DOCTOR software (Able Software Corp., Lexington, MA) using axillar sections of computer tomography (CT) obtained from the Visible human Project. The models were transferred for mesh editing and fixing via VRMesh Studio (Virtual Grid Inc., Bellevue City, WA, USA) software and Rhinoceros 4.0 (3670 Woodland Park Ave N., Seattle, WA 98103 USA); a three-dimensional modeling software was used for 3D structure configuration.

Four different models with different tunnel placements were created to assess the effect of each tunnel positioning on the graft loading. TR was used to determine the tunnel locations, and it is defined as the ratio of the distance from the centre of the tunnels to the lateral clavicle to the length of the clavicle (Fig. 1) [12]. The tunnel location of the primary model (M1) was determined using the mean values (0.225 for conoid tunnel and 0.145 for trapezoid tunnel) of ratios calculated with reference to previous studies which were reported to have low failure rates: 0.20–0.25 for conoid tunnels and 0.13–0.16 for trapezoid tunnels [7, 9]. The locations of medialized and lateralized conoid and trapezoidal tunnels were determined at medial and lateral 5-mm distances from M1 tunnel centres. In the anatomical model (M2), the trapezoidal and conoid tunnels were placed medially from the lateral end of the clavicle at 25 and 45 mm, respectively [6, 11].

The conoid tunnel was placed the posterior aspect of the clavicle, and the trapezoid tunnel was placed the anterior aspect of the clavicle [6]. The tunnel diameters were 5 mm. Following the creation of the tunnels, a tendon model with a diameter of 5 mm was created. The tendon was passed beneath the coracoid process and fixed to the clavicular tunnels (Fig. 2). The created models are defined as primary (M1), anatomic (M2), medialized (M3), lateralized (M4).

The generated 3D models were transferred to ALGOR FEMPRO (ALGOR, Inc., 150 Beta Drive Pittsburgh, PA 15238-2932, USA) software for FEA. The model was transformed into a rigid model as Bricks and Tetrahedra elements. The number of nodes and elements in the models is shown in Table 1.

Boundary and loading conditions

The sternal articular surface of the clavicle and the inferior surface of the acromion were determined for the boundary conditions [17]. Forces were applied to the clavicle at three

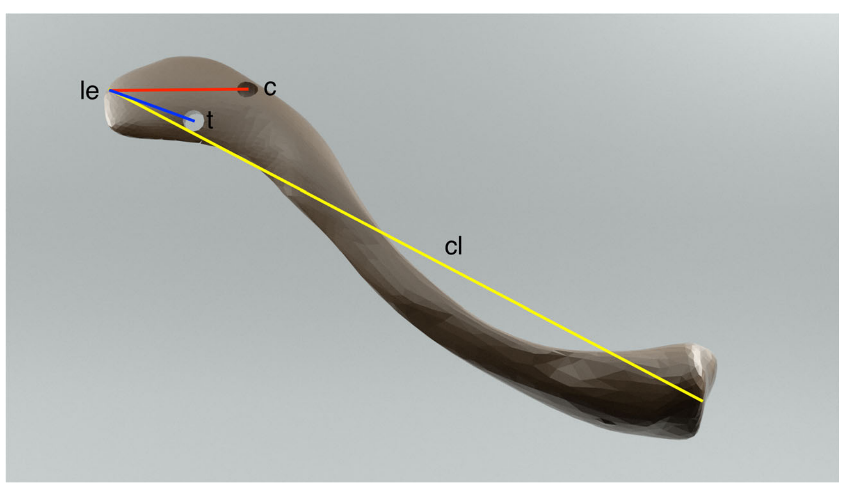

Fig. 1 Tunnel ratio was calculated as dividing by the distance from the center of the coracoid (c) or trapezoid (t) tunnel to the lateral clavicular edge (le) to the total clavicular length (cl)

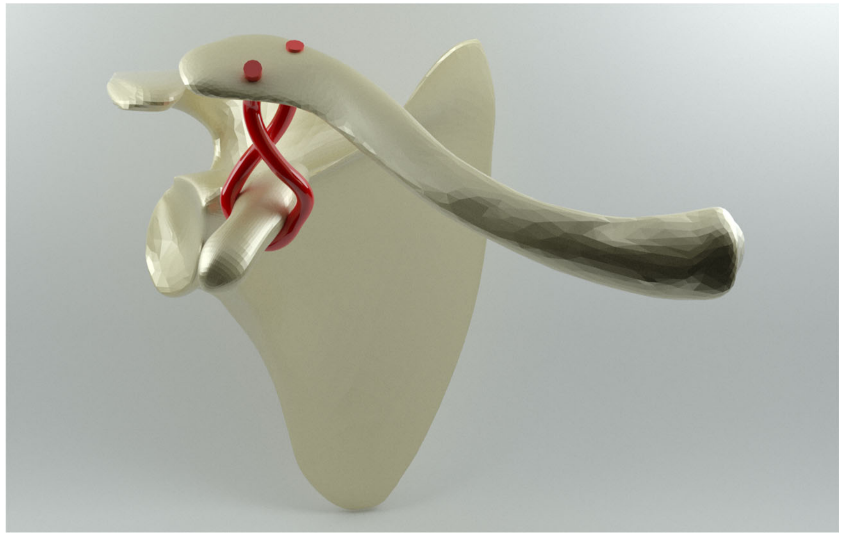

Fig. 2 Antero-superior view of the bone and tendon models

axes from the insertion of the trapezius muscle (X axis: −2.8 N, Y axis: 22.4 N, Z axis: −30.5 N) and the insertion of the sternocleidomastoid muscle (X axis: −1.5 N, Y axis: 14.2 N, Z axis: −4.2 N) [18]. The maximum loads on the tendon graft were calculated as von Mises stress (kPa) [14]. The boundary and loading conditions are shown in Fig. 3.

Material properties

The bones were considered rigid while tendons were nonlinear hyperelastic materials [19]. The values of Young's modulus and Poisson's index for cortical-cancellous bones were used as 17,000–1000 MPa and 0.3, respectively [13]. For Neo-Hookean models, the parameter C10 and bulk modulus (K) values were 19.37 and 17,899 Pa, respectively [20, 21].

Results

The length of the clavicle used in the model was 156 mm. Scenario-based conoid and trapezoid tunnel placements are summarized in Table 2.

Table 1 Number of nodes and elements on models

Model	Name	Number of nodes	Number of elements
M1	Primary	41,910	149,806
M2	Anatomic	41,418	147,249
M3	Medialized	41,527	147,247
M4	Lateralized	41,154	145,805

M1 primary, *M2* anatomic, *M3* medialized, *M4* lateralized

The highest load value measured on the tendon was at M2 (0.789 kPa). The lowest load value was measured at M4 (0.598 kPa). The loading value at M1 was 0.657 and 0.752 kPa at M3 (Fig. 4).

Discussion

The main finding of the current study is that medialized clavicular tunnel placement increases the loading on the graft whereas lateralized tunnel placement decreases the loading in two-tunnel CLR. The second finding of the study is that loading on the graft in traditional anatomic tunnel placement is higher than in other tunnel configurations.

Different surgical techniques such as repair, reconstruction, and reconstruction with augmentation have been described in the treatment of AC joint injuries [1, 22, 23]. The anatomical reconstruction technique is biomechanically superior to the traditional Weaver Dunn technique with minimal recurrent subluxation and residual pain, and it permits early rehabilitation [11, 22]. Failure is one of the main problems encountered in the anatomical reconstruction technique [5, 24, 25]. In recent years, it has been thought that sub-optimal tunnel positioning may be related to failure [5, 7, 9]. The effects of tunnel placement on reconstruction biomechanics have not been discussed in the literature. To the best of our knowledge, this is the first study evaluating the effects of clavicular tunnel placement on loadings.

In the literature, "medialized and lateralized tunnel" terms are not anatomical terms related to clavicular insertion of trapezoid and conoid ligaments. These terms have been used with the reference to the clavicular regions, in which medial or lateral sides of the clavicular

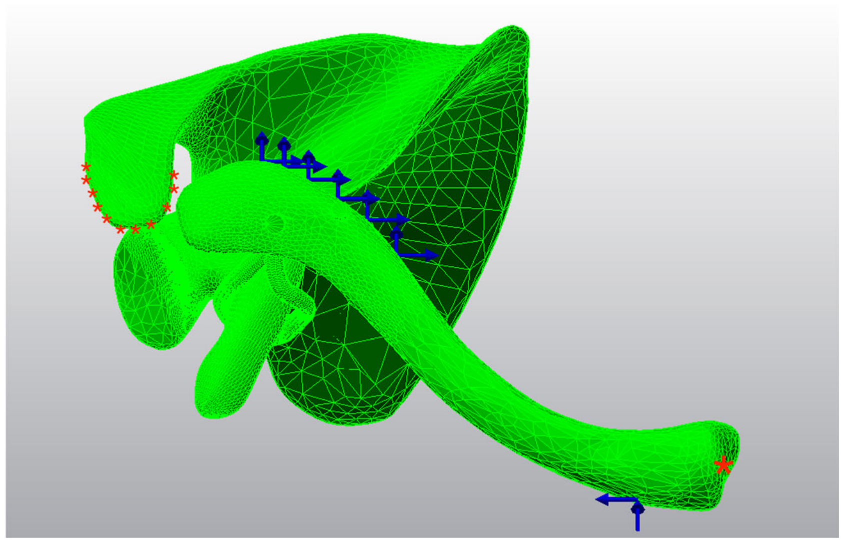

Fig. 3 Boundary and loading conditions. Red asterisk indicates fixation points, and blue arrow indicates applied forces

portion with lower failure rates reported at previous studies [7, 9].

There is limited data in the literature about the relationship between tunnel placement and failure rates. Cook et al. [7] reported on 28 cases with a minimum follow-up of 12 months who underwent two-tunnel CLR and observed that medial placement of the conoid tunnel with a clavicular length of less than 25% was associated with failure. Eisenstein et al. [9] reported on 38 cases with a mean follow-up of 26 months who underwent two-tunnel CLR and observed that conoid tunnel medialization is associated with failure. In the same study, lateral tunnel placement was also associated with failure. In the current study, the loadings on the graft at medialized tunnel placement were calculated to be higher than the primary and lateralized tunnel configurations.

The conoid and trapezoid ligaments limit the superior migration of the clavicle [12]. In the anatomic reconstruction technique, the aim is to restore the biomechanics of the shoulder girdle with the tunnels placed in the anatomic locations of the coracoclavicular ligaments. Traditionally, in the two-tunnel CLR technique, clavicular tunnel locations are defined at a distance of 25 mm medially for trapezoid and 45 mm medially for conoid from the lateral side of the clavicle [6, 10]. In this study, the highest loading values were calculated with anatomical tunnel placement. This may be related to the medial positioning of the conventional anatomic tunnel configuration based on clavicular TR. Therefore, the determination of the tunnel locations by a proportional evaluation may be a more appropriate method for stabilization.

This study has several limitations. Conducting the study using finite element analysis can be seen as the main limitation of this study, because FEA is not able to evaluate repetitive loading conditions, which is one of the reasons for failure in AC reconstruction [25]. Biomechanical studies evaluating the data of cyclic loading and fatigue analysis on cadavers can provide more detailed data on this topic. On the other hand, working on a single model with FEA eliminates the effects of morphological differences on the results by standardizing the tunnel geometry. Furthermore, this study focused on loadings on the tendon, but it should be kept in mind that the failure of two-tunnel CLR may also occur due to bony structures [5, 25, 26].

In this study, the relationship between tunnel placement and tendon loading values was evaluated using the

Table 2 Locations of trapezoid and conoid tunnels

Model	Name	Distance between trapezoid tunnel to lateral clavicle (mm)	Distance between conoid tunnel to lateral clavicle (mm)	Tunnel ratio for trapezoid tunnel	Tunnel ratio for conoid tunnel
M1	Primary	22.6	35.1	0.145	0.225
M2	Anatomic	25	45	0.160	0.288
M3	Medialized	27.6	40.1	0.177	0.257
M4	Lateralized	17.6	30.1	0.112	0.192

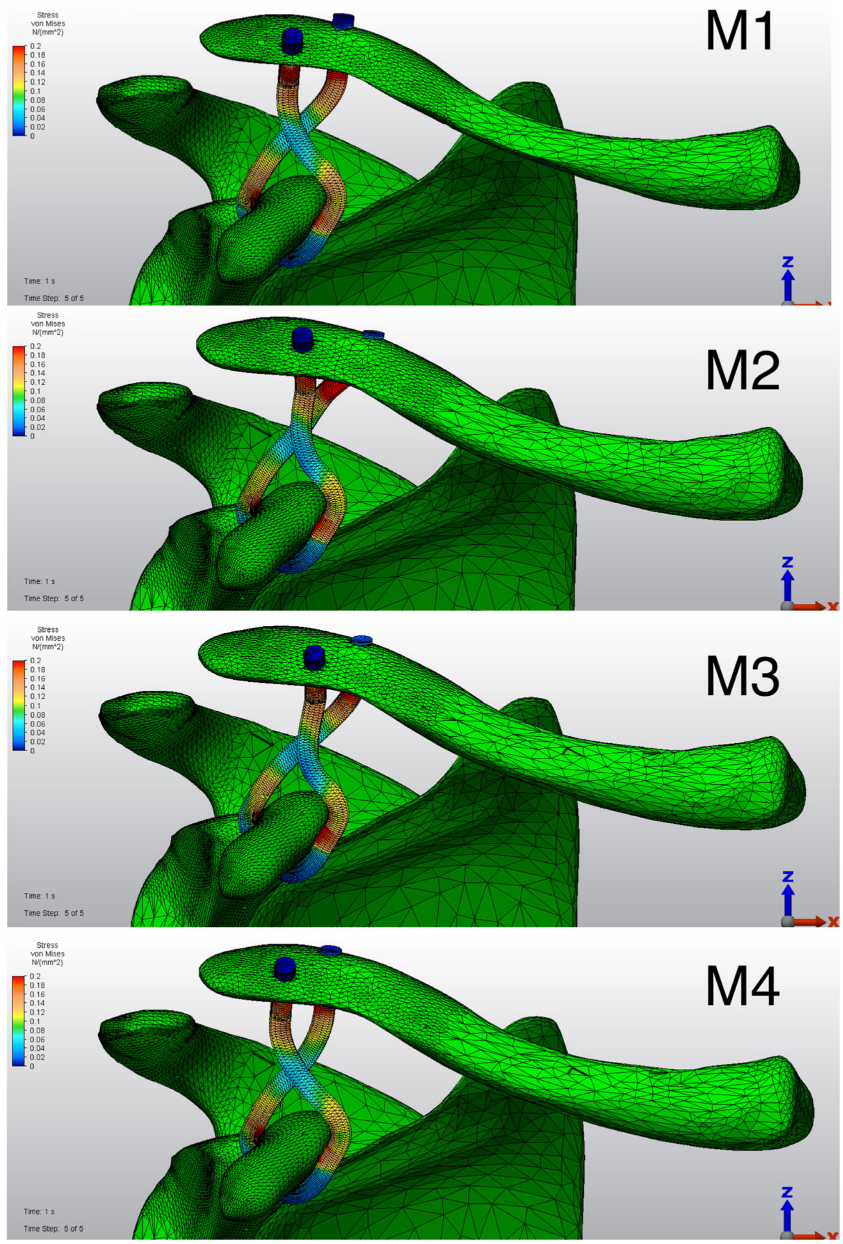

Fig. 4 Finite element analysis and loading distributions on the tendon models. M1 primary; M2 anatomic; M3 medialized; M4 lateralized

two-tunnel CLR technique. The determination of clavicular tunnels according to TR during pre-operative preparation may increase the success of reconstruction. This study also reveals that medialized tunnel placement causes more loading on the graft. Therefore, medialized fixation during surgery may be considered one of the causative factors for post-operative failure.

In conclusion, in the two-tunnel CLR technique, the loadings on the graft are related to the tunnel placement. Tunnel medialization is associated with increased loadings on the graft. There is a need for long-term follow-up randomized studies, involving clinical data, to assess the effect of the tunnel placement on the success of the CLR technique.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This manuscript does not contain any studies with animals or human participants performed by any of the authors.

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