Acta of Bioengineering and Biomechanics
Vol. 20, No. 4, 2018

Original paper
DOI: 10.5277/ABB-01211-2018-03

Evaluation of the plate location used in clavicle fractures during shoulder abduction and flexion movements: a finite element analysis

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Purpose: Plate fixation is a commonly used surgical method in clavicular fracture treatment. The main purpose of this treatment is making the painless shoulder girdle and bring the functions to the optimum level. Plate fixation position still remains controversial. We aimed to investigate the effect of the plate position in clavicle midshaft fractures during shoulder movements. *Methods*: A normal anatomical shoulder joint was modeled using computed tomography images. A fracture line was created on the clavicle. Plate was placed superior to the clavicle in group 1 and anterior in group 2. The impacts of joints, plates, screws, ligaments and clavicle have been shown during 150° flexion and abduction movements of the shoulder by finite element analysis. Analyzes were made non-linear using ANSYS (version 18) and the same boundary conditions were applied in all models. *Results*: The load values in the plate, screws, ligaments, and clavicle were higher in group 1 than group 2 during abduction and flexion movements. Especially the load on the ac ligament was excessive. Load value in the glenohumeral joint was found similar both groups. The load values in the flexion movement were higher than the abduction movement in both groups. *Conclusions*: Anterior clavicle plating provides less stress on material and shoulder girdle, compared to superior plating, during shoulder abduction and flexion movements.

Key words: *acromioclavicular joint, clavicle fractures, plate position, finite element analysis*

1. Introduction

The clavicle is formed S-shaped with the convex at the medial end and the concave at the lateral end. This change of contour, which is most acute at the junction of the middle and outer thirds, may explain the frequency of fractures seen in this area [15]

Clavicle fractures, often seen as a result of falls on the shoulder, occur mainly in young, and active males [17]. The clavicle fractures represent 44% of shoulder fractures and 4% of all fractures [8]. Approximately 80% of the clavicle fractures are in the midshaft region [19]. Most clavicle fractures are treated conservatively. The surgical indications are controversial. If mediastinal structures are at risk because of fracture displacement, multiple trauma and/or "floating shoulder" injuries are present, surgical treatment recommended [20].

Today, active young patients who depend on their upper extremity for daily activities are recommended for surgery. Surgery provides rapid recovery of normal shoulder function [7]. The common surgical treatment is open reduction and plate-screw fixation [4]. The plate fixation enables for early movement by providing rigid stabilization and immediate pain relief.

In the literature there are clinical and biomechanical studies investigating plate position in clavicle fractures. However, finite element analysis studies are limited. There is no study investigating the effect of joint movements in plate position. In this study, we aimed to compare the tensions of the clavicle different plate position in the abduction and flexion movements. High-stress on the joints and

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Received: September 19th, 2018
Accepted for publication: October 23rd, 2018

ligaments restrict the early movement of the shoulder joint.

2. Materials and methods

Geometry and material properties of bone and implant models

In this study, the main model that a healthy person (male, 28 y/o, BMI: 24.1 kg/m, right clavicle, slice thickness: 1.25 mm, per resolution of 512 × 512 pixels) with a normal anatomy was used to create a three-dimensional model of the shoulder by using computerized tomography (CT). CT images of the thorax and upper extremity bones were obtained with no thoracic or upper extremity deformity, using Toshiba Aquilion scanner machine (General Electric, Milwaukee, WI) scanner at the Department of Radiology of Amasya University hospital. Images were recorded in the Digital Imaging and Communications in Medicine (DICOM) format. It was modeled by processing with MIMICS® (Materialize's Interactive Medical Image Control System / Materialize NV, Belgium) an interactive software that uses CT images for visualization and segmentation (Figure 1).

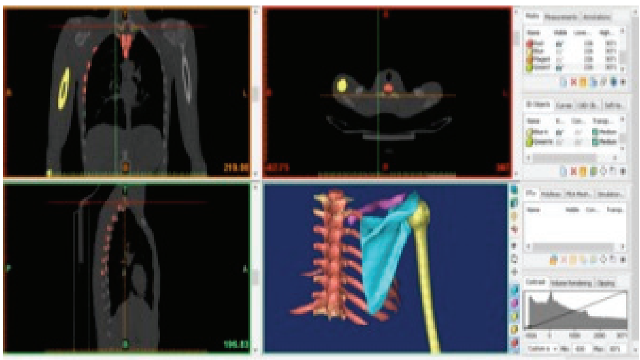

Fig. 1. Models was created by CT images

The geometries from MIMICS software were converted to STL (stereolithography) format and sent to GEOMAGIC® Studio that the reverse engineering software. The surface failure fixing and smoothing of the bio-models to obtain NURBS (Non-Uniform Rational B-Splines) surfaces were performed in GEOMAGIC®. All models were also transferred to SolidWorks® (Dassault Systems, USA) in IGS (Initial Graphics Exchange Specification) format. The ligaments, cartilages, joint and bone and soft tissue models were forming the shoulder with the help of the SolidWorks software. In addition, mid-shaft transverse fracture gap of 1 mm width was created on the clavicle. In our study, the plates and screws used in the clavicle fractures were modeled with their catalog values using Solidworks software, as shown in Fig. 2. Plate fixation was performed superior of clavicle in group 1 and anterior of clavicle in group 2. Six screw holes on anatomic clavicle plate with 3.5 mm in diameter were modelled. The length of the plate was 82 mm and the thickness was 2.5 mm. Plate was fitted parallel in direction of the clavicle and respective superior or anterior contour of the clavicle on the bony surface. The plate was attached to the clavicle by sticking the respective nodes lying at the contact interface. Six locking screws with a diameter of 2.4 mm were inserted perpendicularly to the long axis of the clavicle from distal to proximal.

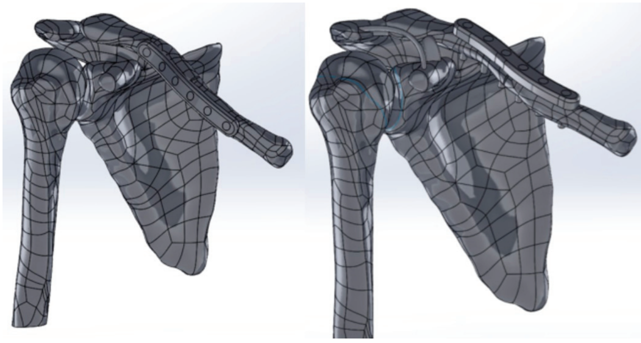

Fig. 2. The placement of the plates in the Solidworks Program: a) anterior position, b) superior position

Mesh and material properties

Using the dynamic analyses in ANSYS® Design Models® (Version 18, Ansys Inc.,USA) software, a mesh was created as seen in Fig. 3 by using Transient analysis. For mesh generation, quadratic 10-node tetrahedral elements were used to form the finite element models. Hexahedral mesh was applied to the cartilage surfaces created in the mesh structure, and tetrahedral mesh was applied to other bones and plate. Models consist of 685962 nodes and 452828 elements on average. Analyzes were performed non-linearly. The non-

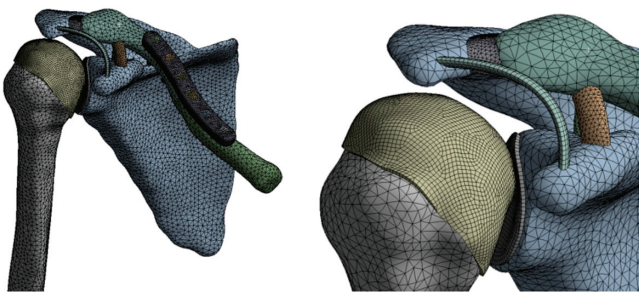

Fig. 3. Finite elements model mesh structure

-linear analysis and dynamic was accomplished in the case of shoulder anterior flexion and abduction action from 0° to 150° in 1 second for all models [3].

A convergence analysis with mesh sizes from 5 mm down to 2 mm was accomplished. In our study, the maximum equivalent stresses on plate and the maximum error energy were considered as convergence criteria.

$$e_i = \frac{1}{2}\int_{\vartheta} \{\Delta\sigma\}^T [D]^{-1} \{\Delta\sigma\} d\vartheta , \qquad (1)$$

were ϑ was the volume of the element, $\{\Delta\sigma\}$ was the nodal stress error, e was the error energy in element i, and $\{D\}$ was the stress/strain matrix. The nodal stress error $\{\Delta\sigma\}$ was the averaged nodal stresses minus the unaveraged nodal stresses.

According to the studies in literature, the model was material properties for cortical bone, cancellous bone, plate (Ti6Al4V) and screws (Ti6Al4V) are defined as linear elastic isotropic material as shown in Table 1 [2]. Ligaments and Cartilages are defined as having viscoelastic properties.

Table 1. Materials properties of bones, cartilage and ligaments

	Young Modulus (E) [MPa]	Poisson Ratio (y)
Scapula	16,000	0.3
Humerus	18000	0.3
Titanium (Ti-6Al-4V)	110,000	0.3
Clavicle	11000	0,3
Humerus cartilage	0,66	0,08
Glenoid cartilage	1,7	0,08
AC joint cartilage	10,4	0,3
Ligaments and capsule	9,6	0,3

Boundary and loading conditions

A transient module of The ANSYS (Version 18, Ansys Inc., USA) program was used for maximum equivalent stress (MES) (von Mises stress) on plate, screws, ligaments, clavicle. After defining the material, contact definition was entered in the model. In the joints, frictionless contact was defined for between the cartilages.

In the case of shoulder abduction and flexion, a dynamic and non-linear analysis was performed between 0° and 150° in 1 second for both models. The MES was recorded under standard earth gravity (G = 9806.6 mm/s^2) with shoulder movements.

Nonlinear dynamic analysis results of the reference, anterior plating, and superior plating models were evaluated by shoulder abduction and flexion movements. Loading on the acromioclavicular ligament, glenohumeral joint, conoid ligament, trapezoid ligament, plate, screws, clavicle surface were calculated according to the plate position in abduction and flexion movements. Reference, group 1 and group 2 models were compared.

3. Results

All loading values of group 1 and group 2 were higher than reference model in shoulder abduction and flexion movements. When we compared group 1 and group 2, all loading values, except for glenohumeral joint, were higher in group 1. The loading in the glenohumeral joint was similar in group 1 and 2. Analysis results in abduction and flexion movements are shown in Tables 2 and 3, respectively.

Loadings on AC joints, plates, screws and clavicle surface were much more excessive in group 1 than group 2 in abduction and flexion movements.

The loadings in the flexion movement were higher than the abduction movement in both groups. MES in the abduction and flexion movements are shown in Figs. 4 and 5, respectively.

Table 2. Analysis results in the abduction movement

	MES* of AC ligament [MPa]	MES of GH Join [MPa]	MES of Conoid ligament [MPa]	MES of Trapezoid ligament [MPa]	MES of plate [MPa]	MES of screws [MPa]	MES of clavicle [MPa]	Life span [Cycles]
Reference Model	0,46745	0,19814	0,60881	1,2731			0,83802	
Group 1	10,909	1,3633	2,2152	2,587	49,666	16,607	10,329	2,1077e+009
Group 2	4,668	1,3632	1,8733	2,154	16,607	7,0894	2,6306	2,1077e+009

* MES: maximum equivalent stress.

Table 3. Analysis results in the flexion movement

	MES* of AC ligament [MPa]	MES of GH Joint [MPa]	MES of Conoid ligament [MPa]	MES of Trapezoid ligament [MPa]	MES of plate [MPa]	MES of screws [MPa]	MES of clavicle [MPa]	Life span [Cycles]
Reference Model	4,7271	0,24253	6,2279	7,3051			4,803	
Group 1	12,4571	2,8874	10,187	10,875	65,785	25,785	16,235	2,1077e+009
Group 2	6,7852	2,874	8,7985	9,875	20,785	12,786	10,87	2,1077e+009

* MES: maximum equivalent stress.

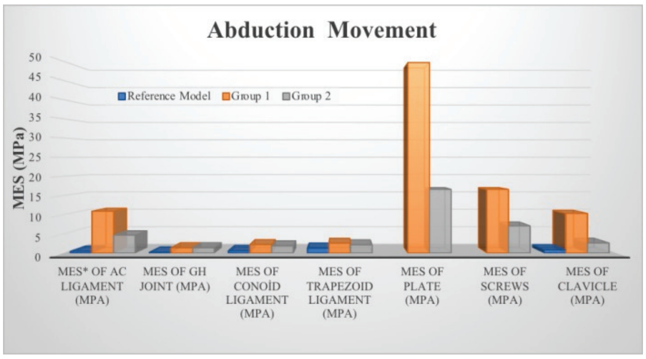

Fig. 4. MES (maximum equivalent stress) in the abduction movement

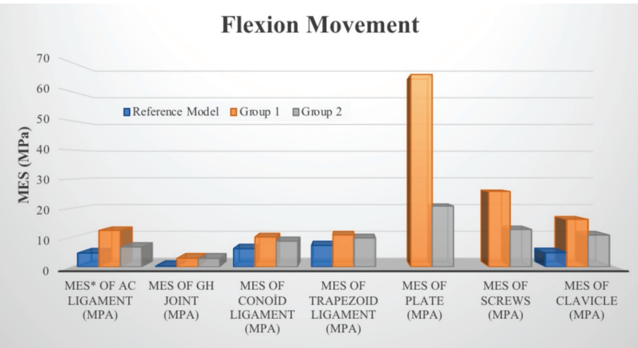

Fig. 5. MES (maximum equivalent stress) in the flexion movement

4. Discussion

Clavicular fractures are common injuries. They occur most commonly in young active individuals [6]. Traditionally, fractures of the middle third (or midshaft) have been treated nonoperatively. Displaced midshaft clavicular fractures have shown a nonunion rate of 15%, which leads to patient dissatisfaction [17].

The surgical indications for midshaft clavicle fractures are controversial. Hill et al. [12] concluded that clavicle fractures with over 2 cm displacement result in patient unsatisfactory, therefore they recommend surgical treatment. There are two surgical techniques used to repair displaced midshaft clavicle fractures: open reduction and internal plate fixation or intramedullary nailing [1]. Open reduction and internal plate fixation have noted a high union rate ranging from 94 to 100% with a low complication rate [10].

Several biomechanical and clinical studies have evaluated plating. In these studies, plate types and plate locations were compared. For plate types, locking anatomical plates is more resistant to axial compression, torsional forces and bending failure than conventional plates [5]. Therefore, we chose the anatomical plate in our study.

Clinically, Nathan et al. [10] found that superior plating can be an irritation of the skin because of the superior plating more superficial. The removal of a few implants has been observed in the anteroinferior plating but not statistically significant. In a systematic review of clavicle fractures, Zlowodzki et al. [21] focused on the anteroinferior position that brought about less postoperative symptoms such as pain.

There are biomechanical studies that investigate the plate position in terms of torsion, cantilever bending, three-point bending, and axial compression [8]. There are conflicting results between these studies. These contradictories may be related to the use of the different test set up, such as plate type, number of point bending test, synthetic or cadaver clavicles bones selection [5], [18], [11], [14]. Partal et al. [18] conducted a study to compare the bone-implant stiffness of superior and anteroinferior plating on sawbone model of a clavicle fracture. Anteroinferior plating on the clavicle provides more stable construct in terms of bending rigidity, compared to superior plating. Harnroongroj and Vanadurongwan [11] plated fresh cadaveric clavicles. The fractures were created at middle clavicle. And they found that if the clavicle has inferior cortical defect, the anterior plating provides more stability than superior plating. Celestre et al. [5] compared plate position in clavicle fractures. They reported no differences in the effect of axial and torsional stiffness with plate location. However, Iannotti et al. [14] found that superior plating maintains a rigid construct in axial and torsional loading.

The finite element analysis studies investigate the biomechanical effects of plate position and plate types [9], [13], [16]. Teng-Le Huang [21] found the lowest plate stress in the anterior clavicle plate model, compared to superior plate and spiral plate. Favre et al. [19] focused on the deformation modes in the anteroinferior plate fixation that were similar in the intact clavicle model and anteroinferior plate fixation provided the best resistance. Cronskär Marie [20] reported that the anterior plating position resulted in lower stresses and the anatomic plate was more stable than regular plate. In our study, we found less stress on the plate, screws and the clavicle surface in anterior plating group.

In the literature there were no studies examining the loading stress on the plate, ligaments, clavicle surface and joint during the shoulder joint motion. In this study, we have used anatomical plate due to its durability. When compared to the reference model, we found high stress on ac ligament after plating during shoulder movements. The tension on the acromioclavicular ligament was excessive in the superior plating, compared to the anterior plating. High-stress on the ac joint may cause pain, and the pain restricts the movement of the shoulder joint.

There are some limitations of our study. Although shoulder has multi-directional movements, the model was created only in two directions. The second limitation is the lack of the muscle forces in our analysis, as only gravitational force was used.

5. Conclusion

As a conclusion, anterior plating represented lower stress on plate, screws, and ligaments, compared to the superior plating during shoulder abduction and flexion movements. We recommend using anterior plating technique based on these advantage in clavicle fracture treatment.

The study was conducted in compliance with ethical standards

The authors declare that they have no conflict of interest.

The authors did not receive any external funding for this study.

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