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ORIGINAL ARTICLE

Can a coracoclavicular screw added to the clavicular hook plate reduce subacromial stress? A finite element analysis

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ABSTRACT

Objectives: The aim of this study was to investigate the stresses on the plate and the clavicle in the standard clavicular hook plate model and the clavicular hook plate models with a coracoclavicular (CC) screw by finite element analysis (FEA).

Materials and methods: The FEA models were created with the combination of acromion, clavicle, coracoid process, 8-hole clavicular hook plate and screw components. Model 1 was created as a standard clavicular hook plate model and plates were implanted to the clavicle and the acromion by six locking screws. Model 2 was created by a cortical screw placed in the coracoid process through the third hole of the plate (CC screw) and fixation of hook plate by five locking screws. The upward-pull force was applied to clavicle at the insertion of sternocleidomastoid muscle with three axes. The stress exerted by acromion on the hook of the plate, stresses on the plate, clavicle, and CC screw were analyzed.

Results: When the screw holes were compared, in Model 1, the highest stress was found in the last hole of the plate. In Model 2, the highest stress was detected on the CC screw. The stress on the clavicle was found to be 0.14 Mpa in Model 1 and 0.21 Mpa in Model 2. In Model 1 and Model 2, the stress exerted by acromion on the subacromial part of the plate was found to be 2.05 KPa and 1.66×10-6 KPa, respectively.

Conclusion: The results of this study show that addition of CC screw to the standard clavicular hook plate shares the loading and reduces the stress on the hook of the plate.

Keywords: Acromioclavicular joint dislocation, clavicular hook plate, coracoclavicular screw, finite element analysis.

Acromioclavicular (AC) joint injuries are common in active young adults and account for approximately 9% of all shoulder girdle injuries.[1] According to Rockwood classification system, type 1 and type 2 injuries are treated non-operatively, but the management of type 3 injuries is still controversial. Type 4-6 injuries are treated operatively due to instability; however, optimal treatment remains matter of controversy.[2,3]

The main goal of surgical treatment is anatomic reduction and stable fixation of the joint, and many treatment methods have been defined to achieve satisfactory results. Operative techniques can basically be divided into two as coracoclavicular (CC) fixation and AC fixation.[3,4] Screw fixation between distal clavicle and coracoid process after open reduction of dislocated AC joint was first described by Boardman Marsh Bosworth.[5] Although this method has been used for a long time in the treatment of AC joint dislocation, loss of reduction, screw breakage or migration can be often seen as complications.[6-9]

Currently, one of the most commonly used AC fixation methods is clavicular hook plate (CHP). The advantage of this plate is to protect the AC

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joint against horizontal, vertical and rotational forces. However, complications such as subacromial osteolysis, impingement syndrome, acromion cut-through and acromion fracture can be seen after CHP application.[9-13] Most of the complications about CHP is likely to be related to unopposed vertical forces on this implant. In the present study, we hypothesized that adding a screw between clavicle and coracoid process, which is inserted from one of the holes of CHP, should neutralize the forces acting on under surface of acromion.

The finite element analysis (FEA) is frequently used in the biomechanical analysis of orthopedic implants.[14-19] It has previously been used to investigate the effects of different designs of CHPs on the acromion and clavicle.[14-16] In the present study, in addition to the model created using the standard hook plate, we constituted a new model with an additional cortical screw placed in the coracoid process through the third hole of the hook plate (CC screw) and aimed to investigate the stresses on the hook of the plate in both models with FEA.

MATERIALS AND METHODS

This finite element analysis was conducted at Tepecik Training and Research Hospital, Department of Orthopaedics and Traumatology and Yozgat Bozok University Faculty of Engineering, Department of Mechanical Engineering. Three-dimensional (3D) computed tomography scans were used to create clavicle and scapular bone models. A 3D-assisted design (CAD) software program (SpaceClaim 2020R2, ANSYS, Inc., PA, USA) was used to draw the models of the 8-hole CHP, cortical, and locking screws. The FEA models were created with the combination of acromion, clavicle, coracoid process, hook plate and screw components. Model 1 was created with the implantation of an 8-hole hook plate (18-mm hook depth, 90° hook angle, titanium alloy) to the clavicle and the acromion by six locking screws (Figure 1a). Model 2 was created by a cortical screw placed in the coracoid process through the third hole of the plate (CC screw) and fixation of hook plate by five locking screws (Figure 1b). Once the 3D models were created, they were uploaded into

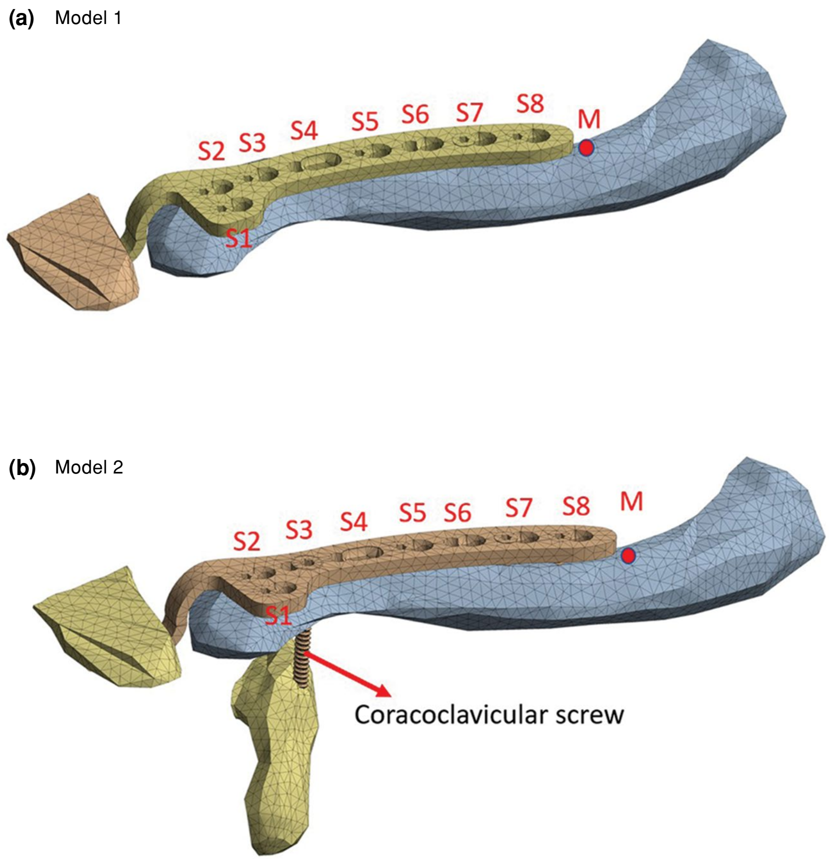

FIGURE 1. (a) Finite element model of 8-hole clavicular hook plate (Model 1) and **(b)** 8-hole clavicular hook plate with coracoclavicular screw added (Model 2).

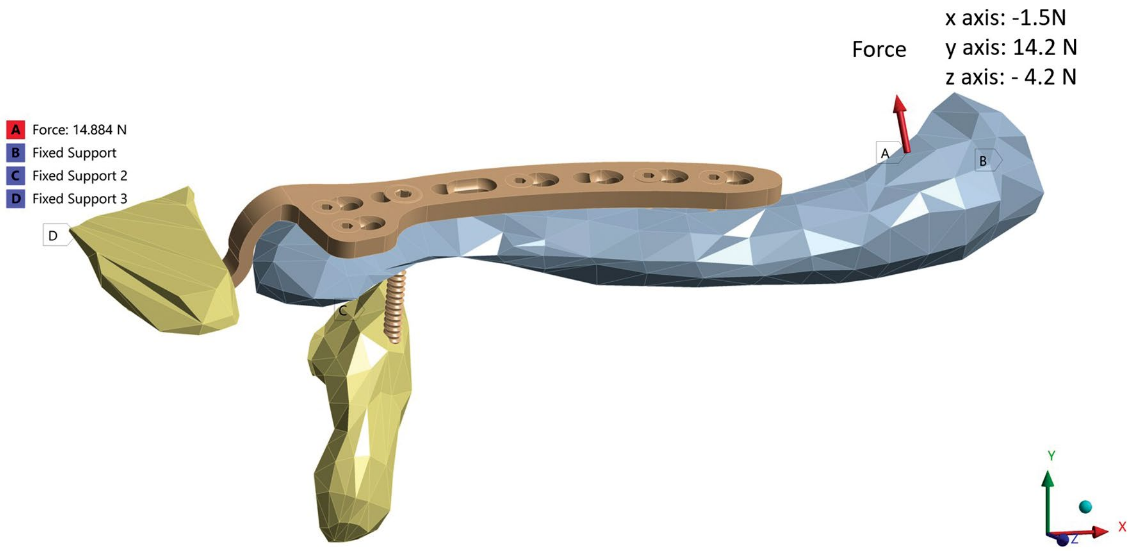

FIGURE 2. Loading and boundary conditions.

a software program (ANSYS Workbench 2020R2, ANSYS, Inc., PA, USA) to constitute FEA models and to perform static transient FEA. Higher order tetrahedral solid elements were used in the model. To achieve the best results, mesh optimization was performed and the best mesh density was identified. First, the model is meshed by default of program. It is usually a coarse mesh. According to

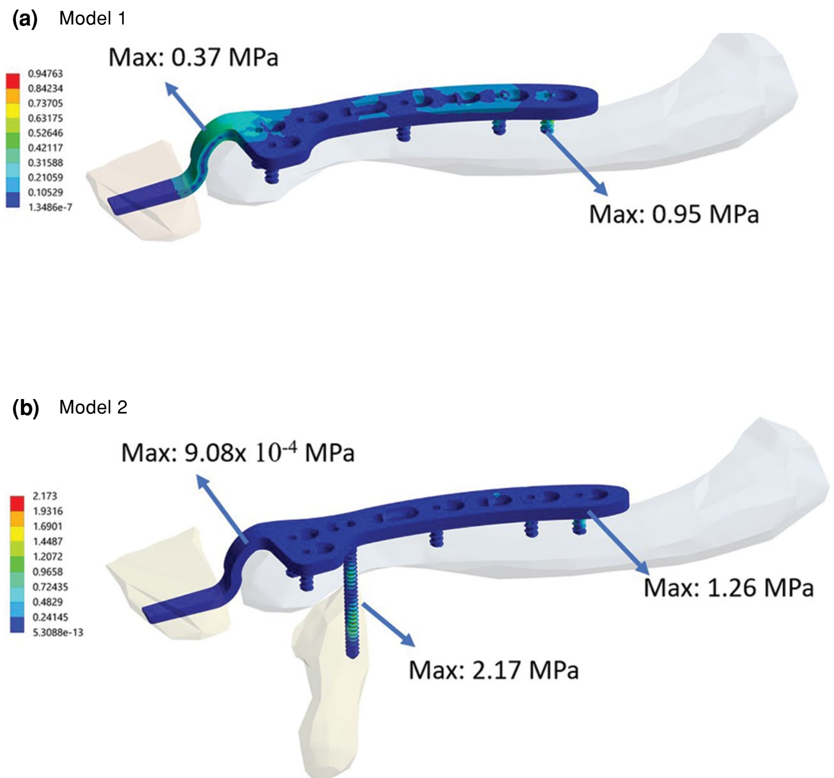

FIGURE 3. von Mises stress distribution on clavicular hook plates **(a)** Model 1 and **(b)** Model 2.

TABLE I
Maximum von Mises stress values (MPa) on clavicular hook plates and clavicles (M point)

	S1	S2	S3	S5	S7	S8	Bent portion of plate	Hook of the plate	Clavicle (M point)
Model 1	0.11	0.55	0.25	0.22	0.44	0.95	0.37	0.02	0.39
Model 2	0.05	0.06	2.17	0.37	0.29	1.26	9.08×10^{-4}	1.66×10^{-9}	0.51
Percent changes between the models (%)	-54	-89	+768	+68	-34	+32	-99	-100	+30

the results, it is refined. When there is no significant change in the results by changing mesh resolution, it refers to the best mesh; i.e., mesh optimization. In this study, the element length was 3 mm.

The loading and boundary conditions were applied as previously described and used.[15,16] The lower ends of the medial clavicle and under surface of acromion were designated as the boundary conditions. The upward-pull force was applied to clavicle at the insertion of sternocleidomastoid (SCM) muscle with three axes depending on time as ramped (X axis: -1.5 N, Y axis: 14.2 N, Z axis: -4.2 N) and when the forces were applied, the clavicle could rotate (Figure 2). The plate was placed and there was no gap between the hook of the plate and the acromion. Interface of them was thought as frictional contact and friction coefficients and chosen as 0.2.

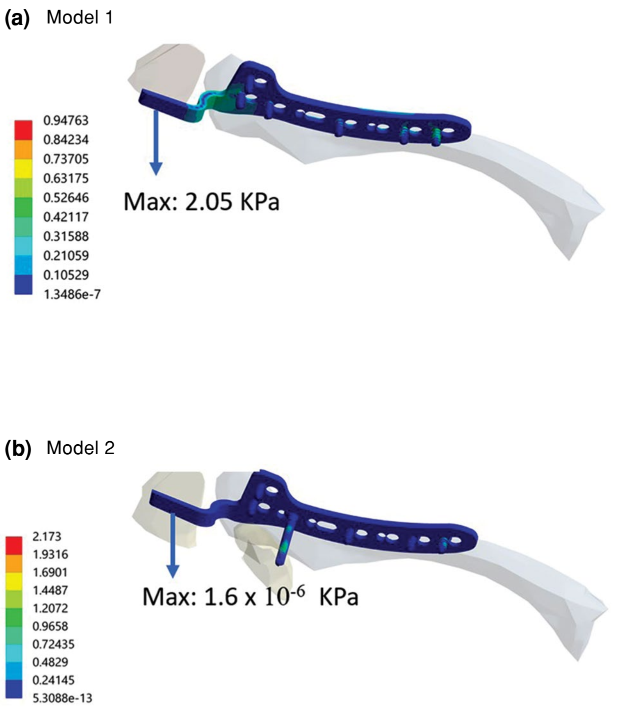

FIGURE 4. von Mises stress distribution on the hook of the plate **(a)** Model 1 and **(b)** Model 2.

All materials used were presumed to be isotropic and homogeneous.[17] The properties of the materials are indicated by the Young's modulus (E) and Poisson's ratio (ν). The clavicle plate and screws were made of titanium alloy (Ti-6A1-4 V) (E=110000 MPa and ν=0.3). The values of the Young's modulus and Poisson's index for cortical bone were used as 17000 MPa and 0.3, respectively.[15,16]

After applying FEA, the stress exerted by acromion on the hook of the plate, the von Mises stress distribution on the hook plate, the stress on the clavicle just at the end of the plate (M point), and the stress on the CC screw were analyzed. The values found were compared between the two models.

RESULTS

Figure 3 demonstrates the von Mises stress distribution on the clavicle hook plates. In Model 1, the highest stress was found at the turning portion of the plate. When screw holes were compared, the highest stress was found in the last hole of the plate (Table I). In Model 2, the highest stress was detected on CC screw. The stress on the turning portion of the plate was much less compared to this screw. Among all other screw holes, the highest stress was found in the last hole in this model, as well (Table I).

In Model 1 and Model 2, the stress exerted by acromion on the subacromial part of the plate was determined as 2.05 KPa and 1.66×10^{-6} KPa, respectively (Figure 4).

Figure 5 shows the von Mises stress distribution on the clavicle. The stress at the M point was found to be 0.39 Mpa in Model 1 and 0.51 Mpa in Model 2.

When the forces in three planes were applied to the proximal clavicle, a maximum displacement of 7.38×10^{-3} mm in Model 1 and 1.44×10^{-3} mm in

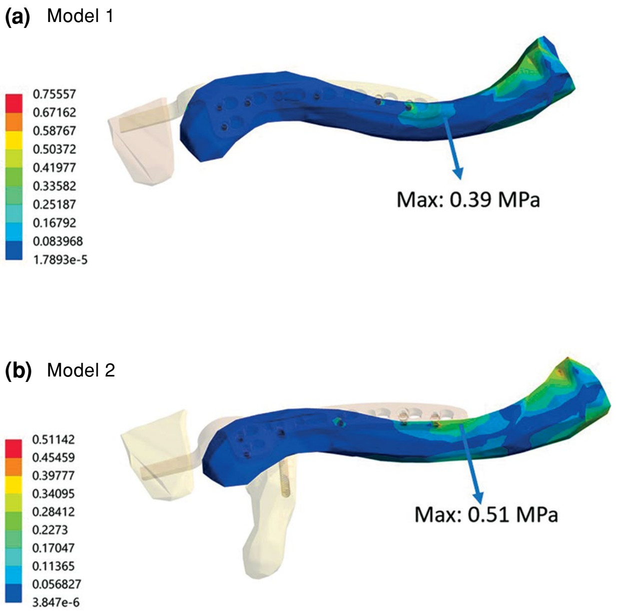

FIGURE 5. Distribution of von Mises stress on the clavicle **(a)** Model 1 and **(b)** Model 2.

Model 2 was observed at the distal clavicle in the sagittal plane.

DISCUSSION

The main finding of present study is that adding a CC screw to the CHP can reduce the stress exerted by the acromion on the hook of the plate. Another important finding is that the application of this screw can increase the stress on the holes of the plate and on the midpoint of the clavicle. These results showed that our hypothesis was partially confirmed.

Coracoclavicular fixation with a CC screw is a reliable method used in the treatment of AC joint dislocation.[5-9] Biomechanical studies have shown that it is a very rigid fixation method.[20] Complications such as loss of reduction, breakage or loosening of the screw can be observed during follow-up.[6-9] Of note, CHP is a less rigid system that has been widely used in the treatment of AC joint injuries.[20] However, complications such as acromial osteolysis and fracture can be seen in the mid- and long-term clinical follow-ups.[10-13] To reduce these complications, clavicle hook plates with different depths and different hook angles have been designed. Lee et al.,[14] in their FEA, showed that deeper implantation of the CHP reduced the stress on the clavicle and the forces exerted by the CHP on the acromion. Hung et al.[15] investigated the biomechanical effects of different hook angles of the hook plate on the AC joint with FEA and reported that the wider-angle hook plate caused less stress in the middle of the clavicle. However, they observed that as the hook angle increased, the force under the acromion also increased, suggesting that the main reason is that a larger hook angle makes the contact position between the clavicle hook plate and the acromion more proximal. Although the hook plates with different features are commercially available, aforementioned complications can be still seen.[10-13] In the current study, we attempted to combine the advantages of the AC and CC fixation methods in our model and we believe that this model can prevent or reduce these complications.

Shih et al.[16] investigated the biomechanics of different sizes of hook plates made of different materials and compared 6- and 8-hole plates in their FEA. They showed that short hook plates made of titanium alloy cause higher stress in the middle of the clavicle. In our study, we used 8-hole plates made of titanium alloy, and the highest stress was found on the last hole of the plate. We also detected that the stress just medial to the plate on the clavicle was higher, when the CC screw was used in the plate. This can be explained by the shortening of the force arm of the plate, as the hook plate was fixed to the coracoid process with a cortical screw. Although Shih et al.[16] reported that stress on the clavicle could lead to peri-implant fractures, there are few peri-implant fractures in the literature and all of them developed after new traumas.[10,21]

In the present study, when the hook plate was fixed to the coracoid with a cortical screw and force was applied in three planes to the proximal of the clavicle, the movement in the distal clavicle decreased. Although the deterioration of the physiological movement of the clavicle can be considered a handicap, it may prevent getting rid of the hook from the acromion, which was reported as a complication in a number of studies.[10-12]

When the stress on the whole plate is investigated, in Model 1, the highest stress was found on the bent portion of CHP, as in the studies of Shih et al.[16] and Hung et al.[15] The stress on the CC screw was found to be more than the bent portion of the plate. This indicates that the CC screw takes most of the load. In case of screw loosening, which is one of the complications of CC screw use, it can be predicted that the hook plate would take over most of the load. We believe that this load sharing may cause less osteolysis in the acromion, until the healing of the AC joint is completed.

In our study, von Mises stress values on both the clavicle and hook plate were found to be lower than the other studies.[14-16] This can be explained by the use of different shoulder models and the differences in plate placement. The subacromial peak stress was found to be lower and at the same time a more uniform stress distribution was observed in CC screw added model. All these findings suggest that this model may reduce acromial osteolysis and prevent acromial cut-through.

Chang et al.[11] compared the outcomes of CHP fixation with or without CC tape augmentation for the treatment of acute AC joint dislocation. They found less radiological subacromial osteolysis and better functional results in the hook plate with CC augmentation group. Based on the results they obtained, it can be speculated that when the coracoid and clavicle are fixed together in addition to the hook plate fixation, the hook of the plate causes less stress on the under surface of the acromion. We also planned our study with this foresight and we proved our hypothesis with FEA. Although the CC screw added to the hook plate seems to share the load and reduce subacromial stress, this must be demonstrated in clinical studies.

To the best of our knowledge, there is no other study in the literature evaluating the stresses on the plate by adding the CC screw to the CHP.[22] In our study, it was thought that modeling the medullary bone separately would not contribute additionally, and the bone model was designed as a homogeneous cortical bone. The fact that the area where the acromion exerts stress on the plate was formed by cortical bone and that all the screws used were placed between the plate and the cortical surfaces were influential in this decision. The discrepancy of stress values between the present study and the literature data can be as a result of this modelling difference. In addition, the use of different models and programs and the discrepancy in the mounting of the plate to the bone model may cause differences between the stress values which we obtained and in previous studies. Therefore, it is more reasonable to compare the stress values between our two models and discuss this issue. Although there are differences in the stress values in this study and in the literature, the proportional stress reduction in the model with CC screw is quite significant.

Our study has several limitations. First, FEA is associated with many limitations. In the created model, most of the scapula was removed and only the acromion and coracoid process were included to the model and biomechanical analyses were made only for the clavicle, hook plate, coracoid process and acromion. The clavicle was loaded only with the SCM muscle, and the effects of the movements of the scapula and other muscle forces on the clavicle and hook plate could not be analyzed. Although these are considered as shortcomings, our main objective in this study was to evaluate the stress occurring on the hook of the plate in both models as a result of constant forces applied to the clavicle. Second, FEA is able to make static assessment; therefore, issue repetitive loadings that may cause osteolysis on the acromion were unable to be evaluated. Biomechanical studies evaluating cyclic loading in cadaver specimens may provide more detailed information about this subject. Nevertheless, although there are differences between representative and real-life circumstances, this study may inspire and shed light on future clinical studies.

In conclusion, the situation that causes orthopedic surgeons to hesitate mostly in the use of the CHP is that the muscle forces acting on the hook of the CHP which may cause erosion and even fracture of the acromion. The results of the present study show that addition of CC screw to the CHP shares the load and reduces the stress on the hook and bend portion of the plate. Adding a CC screw to the fixation would reduce complications related to acromion.

Ethics Committee Approval: The study protocol was approved by the Tepecik Training and Research Hospital Ethics Committee (date: 16.11.2020, no: 2020/13-16). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Material preparation and data collection: M.K., A.Ö., M.B.; Supervision: A.T., Data collection and processing: A.Ö., M.K., M.B., Analysis and/or interpretation: A.Ö., M.K., Literature search: M.K., M.B., A.T., Writing manuscript: M.K., A.T., Critical review: A.T., A.Ö.

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