# Modeling of fractured clavicles and reconstruction plates using CAD, finite element analysis and real musculoskeletal forces input

M. Cronskär & M. Bäckström
*Mid Sweden University, Sweden*

## Abstract

This study focuses on the treatment options for clavicle fractures, more specifically the cases with a need for internal fixation: non-unions and some complex fractures. Enhancing the understanding of the loading of the bone and fixation device enables treatment options to be improved. The aim of the study was to develop a method for the realistic simulation of stresses and displacements in the bone and fixation device and to use this method to make comparisons between a conventional reconstruction plate and a customized plate, designed from patient-specific computed tomography (CT) data. In an earlier study, a finite element (FE) mesh of the clavicle geometry was created from CT data, subjected to muscle forces and other boundary conditions from a multibody musculoskeletal model and imported into the FE solver. In this study, a solid 3D model of the same clavicle geometry was created and the mesh was replaced by the solid model to make the FE-model more suitable for the comparison of different plates. An LCP Reco-Plate 3.5 straight, 6 holes (by Synthes) was compared with a customized plate which was designed to follow the anatomy of the bone. The LCP-Reco plate has tapered reconstruction segments throughout the plate to allow for the plate reshaping during surgery. The customized plate was designed without such segments and with a lower width than the LCP plate. The two different plates showed stresses and displacements of similar magnitudes. The customized plate had a more even stress distribution while the LCP plate had higher stress concentrations in the middle of the plate and on the edges of the tapered reconstruction segments. To the authors' best knowledge, this is the first FE model of a clavicle bone with plate and it may, upon further development, serve as a useful instrument for improved clavicle fixation.
*Keywords: clavicle, finite element analysis, CAD, modeling, bone plate.*

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# 1 Introduction

Previous research has highlighted how treatment of clavicle fractures differs between countries and with differing types of fracture [1, 2] (both non-operative and operative results are shown in studies). The predominant way of treating clavicle fractures is the non-operative strategy. This is mainly based on tradition, but also reflects how there are no science-based uniform directions for best practice at hand. However, some of the clavicle injuries are chosen to undergo surgery due to the high risk of lasting dysfunctionality. It is typically badly healed injuries resulting in non-union, malunion or sequelae that justify the need for an operation. In addition to these cases there are also some complex fracture traumas that are always operated. Overall, the non-operative strategy is preferred in some studies [3–5], while other studies report the downsides of non-operative treatment that results in disfunctionalities [6–8].

In cases when an operation is considered the best treatment option, more issues need to be dealt with. Some of these issues can be resolved during preparation for surgery and some have to be handled during the operation. A set of standard plates is commonly arranged in the operation theatre for the fixation of the fractured bone. Often, different kits from one or more vendors of medical equipment are to be used. The kits are compiled to deal with many fracture types and severities. The plate is typically selected when the fracture is exposed and an assessment of the geometrical need is performed during the operation. Based on this assessment, the best plate is selected; extensive modifications to this plate are, in most cases, necessary to accomplish an acceptable fit. Valuable time is thus spent in the operating room with the patients under anesthetic and the wound open and it is often hard to create the optimal fit to support the fracture [2].

The current options for operative treatment are intramedullary devices, reconstruction plates which require shaping during surgery to follow the bone contour and anatomically-shaped plates which are pre-contoured to follow the shape of an average clavicle. The fitting problem is solved by using customized plates, but questions remain about their structural integrity compared to standard fixation devices. Therefore, a study has been conducted to compare an LCP Reco-Plate 3.5 straight, 6 holes (by Synthes) with a customized plate using solid CAD modeling and FE methodology.

# 2 Materials and methods

## 2.1 Background

This study is a continuation and development of the work reported earlier [9]. In this study a bone mesh was created from computed tomography (CT) data of a 36-year-old woman's clavicle bone. The CT data was converted into a *.stl (stereolithography) mesh file using Mimics 14.11 (by Materialise) and a fracture was simulated on the bone mesh using the Magics 16.0 software (by Materialise). An LCP Reco-Plate, 6 holes, was scanned using a FARO Titanium measurement arm with laser scanner; a 3D CAD (computer aided design) model was then created and digitally contoured to fit the bone mesh. The plate and corresponding screws were used to create matching holes in the bone mesh.

The adapted clavicle model, including the fracture gap and screw holes, was imported into the AnyBody Modeling System (by AnyBody Technology, Aalborg, Denmark) and subjected to a multi-body musculoskeletal analysis based on inverse dynamics, assuming a third-order muscle recruitment criterion. A static arm position, holding a 0.5 kg weight in front of the mouth was used in the simulations. For details on the musculoskeletal simulation method, please refer to Damsgaard *et al*. [10].

The FE analysis was performed with the FE software package Abaqus 6.11 (by Dassault Systems) into which the input file containing the bone-mesh with loads from the biomechanical model was imported. The plate and screws were imported as IGES files, and assembled and oriented to fit the bone mesh (see figure 1). The method for creating the FE model, including the bone mesh generated from CT data and a load case based on a multi-body musculoskeletal model generated in the AnyBody software, is presented step by step in [9].

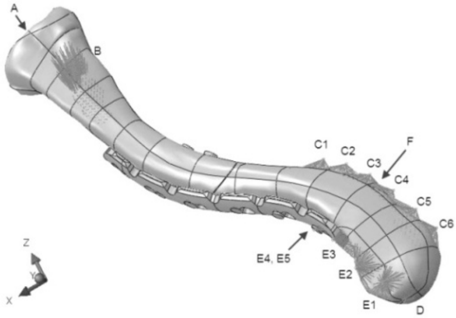


Figure 1: FE model of bone with plate and screws, with muscle and ligament attachment areas. See table 1 for the specifications of the labels A to F and corresponding forces. The labels with arrows are the muscle and ligament attachments that are not visible in this view.

Table 1: Muscle and ligament forces [9].

| | Muscle force components (N) | | |
|---|---|---|---|
| Muscle/ligament | Fx | Fy | Fz |
| Lig. Conoid (F) | -86,8 | - 84,8 | -11,5 |
| Lig. Trapezoid | 0 | 0 | 0 |
| M. Deltoid (E) | 59,2 | -46,8 | -25.8 |
| M. Pect. major | 0 | 0 | 0 |
| M. Sternocleidomastoid (B) | - 4,2 | 14,2 | -1.5 |
| M. Trapezius (C) | - 2.8 | 22,4 | 30,5 |
| Sternum contact force (A) | 11,1 | 13,4 | -10,1 |
| Acromion contact force (D) | 23,4 | 86,5 | 18,3 |

### 2.2 Development of the FE model

While building the previous FE model, it appeared that a lot of work is required to be able to use the model for calculations with alternative fixation devices. The mesh has to be modified to suit the screw positions of the new fixation device, which entails a new musculoskeletal simulation. So, another round of mesh modifications for FE analysis and additional work in the FE solver is needed. To make it easier to perform comparative studies, the FE model was adjusted to better meet those requirements.

A solid 3D CAD model of the clavicle geometry was developed using RhinoResurf (by Rhinoceros 4.0 McNeal North America, USA). The solid model was imported into the previous FE model and oriented in the same position as the present bone mesh (including muscle forces). The solid bone model can be modified to suit different fixation devices using boolean operations to create matching screw holes. It is then meshed in the FE solver and the muscle and ligament forces are coupled (using Abaqus) to the new mesh instead of the old "orphan mesh". This means that the same FE model can be easily modified to suit different fixation devices using the same musculoskeletal simulation. Another advantage of this model is that it is also possible to vary the type of fracture in the same manner, in order to simulate stresses in the fixation devices, dependent on the fracture type.

### 2.3 FE model

The bone was meshed with quadratic (10 nodes) tetrahedral elements with a total number of 61,283 (91,837 nodes). The screws and the two fixation plates were also meshed with a quadratic tetrahedral mesh. There are 41,891 elements (66,969 nodes) in the LCP Reco plate and in the customized plate there are 46,081 elements (72,690 nodes). The screws were meshed with around 2,000–3,000 elements per screw (6,000-7,000 nodes).The upper sections of the screws were modeled with a coupling constraint (Abaqus) to the inner surface of the plate holes. The lower sections of the screws were coupled to the surfaces of the screw holes in the bone mesh. All linear translations and the rotation around the axis along the clavicle bone were locked with a boundary condition assigned to a small surface of the medial end of the bone. At the distal end, the linear translations were locked in the transverse directions in the same manner. The largest reaction force in the boundary conditions was 3.7 N, demonstrating that the muscle and ligament forces are almost in equilibrium. In the previous mesh model a surface-to-surface contact interaction was modeled in the fracture gap. The surfaces in the fracture gap did not interfere in the simulation and hence the contact interaction has been excluded from this model.

An anisotropic material was assigned to the clavicle bone with a Young's modulus of E=18 GPa in the longitudinal direction of the bone and E=8 GPa in the transversal direction [11]. The Poisson ratio was 0.3. The plate and screws were assigned a stainless steel (316 L) material, E=186.4 GPa and Poison ratio 0.3 [12].


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### 2.4 Comparison

The FE model was used to compare stress distributions and displacements in bone and plates for two different fixation plate solutions: one commercial LCP Reco-Plate 3.5 straight, 6 holes, and one customized plate that was designed by us and based on patient-specific computed tomography (CT) data. This paper will only present the stresses and displacements in the plate, and not in the bone geometry.

The previously created *.stl file for the clavicle bone was imported into the Rhinoceros 4.0, where the customized plate was modeled to follow the clavicle bone geometry, with three holes on each side of the fracture. Since the plate will follow the anatomy of the actual patient’s clavicle there is no need for the tapered reconstruction segments used to shape the plate during surgery. Instead, the customized plate is designed with a smaller width. The width of the LCP plate is 10 mm and that of the customized is around 7 mm. The customized plate is more cup-shaped around the bone (see figure 2).

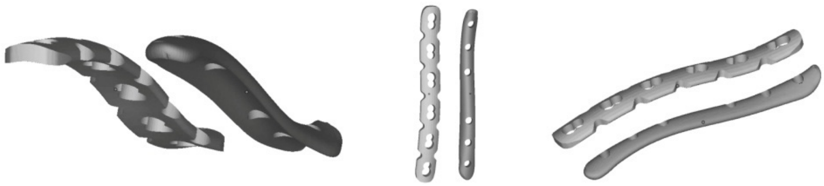

Figure 2: The geometry of the two plates in the study.

## 3 Results

There were small differences in the resulting Von Mises stresses and displacements between the old “orphan-mesh” model and the new model, based on a solid CAD model of the clavicle. The differences are presented in fig 3. The maximum stress in the individually designed plate was around 350 Mpa (fig. 4) and was localized around the hole edges at the bottom of the plate. In the LCP Reco plate, the corresponding maximum stress was around 440 Mpa and is localized at the edge of the tapered reconstruction segment. The stresses were more evenly spread on the customized plate compared to the LCP Reco plate. The maximum displacement on the individually designed plate was 0.78 mm, which can be compared to 0.53 mm in the LCP plate. In one of the screw holes there was a local stress concentration at a point in the middle of the screw hole’s surface, overriding the above mentioned highest stress. The authors assume that this stress concentration is derived from the characteristics of the coupling constraint. This issue has to be further analyzed in future work.

 
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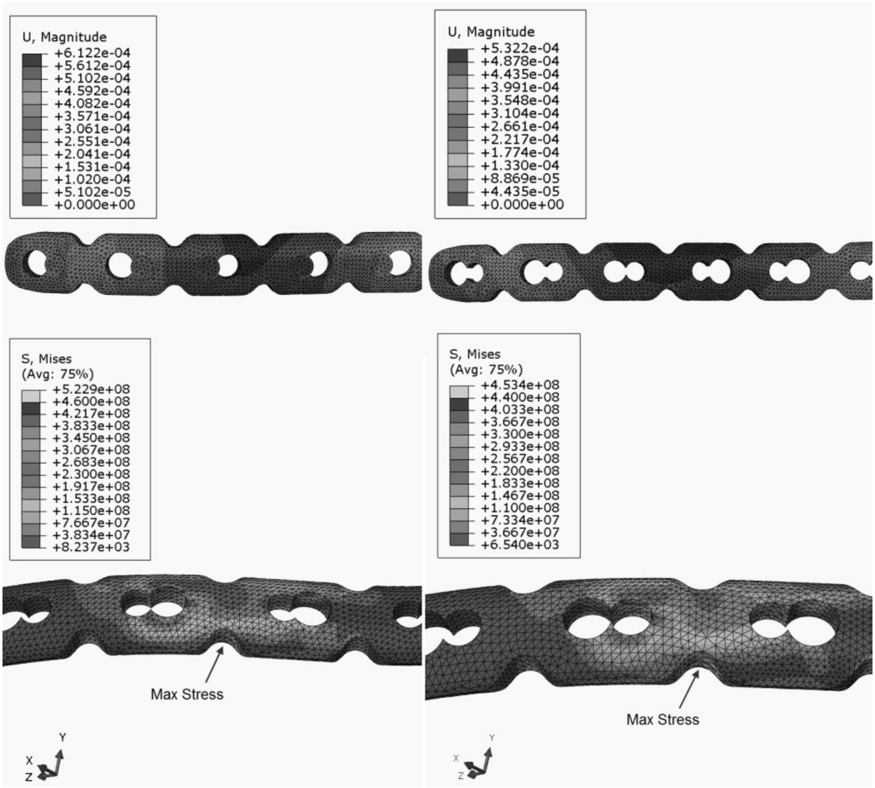


Figure 3: Resulting stresses and displacements in the mesh model to the left, and in the solid model to the right.

## 4 Discussion and conclusions

The treatment of clavicle fractures varies greatly between countries [1]. There are also differing opinions about the optimal treatment of the various types of fractures. Furthermore, the shoulder region is a complex area with many muscles, ligaments, bones and associated joints, which leads to a complicated interplay of factors that determine the main stresses in the bones. Thus, practical in vivo trials and experimental tests on loads and strains, on fixation plates are difficult to perform and reliable simulation techniques are necessary.

To the authors' best knowledge, this is the first FE model of a clavicle bone with a fixation plate. Most of the previous work has been performed with simplified models of the loading situation, and on the clavicle bone alone. Previous biomechanical studies and plate failure studies of the clavicle have used varying and often greatly simplified load cases, such as axial compression or

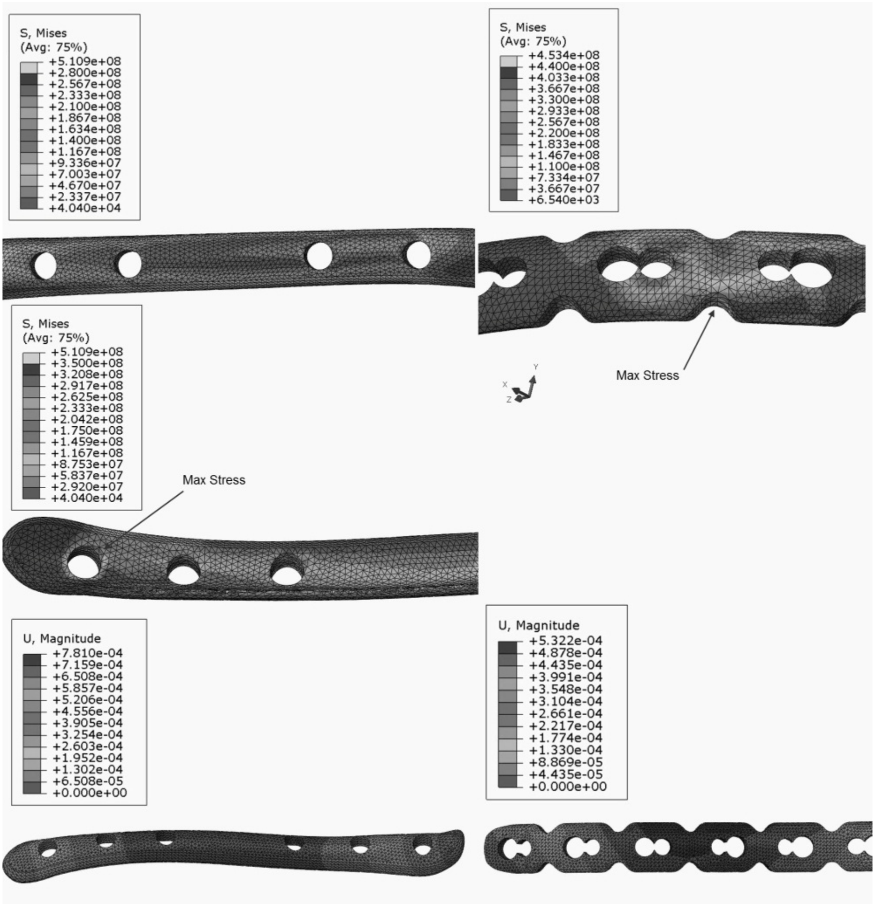


Figure 4: To the left: stresses and displacements in the individually designed plate. To the right: stresses and displacements in the LCP Reco plate.

cantilever bending. Earlier studies including FE analysis of clavicles mainly concerned injury predictions [13, 14] and the authors have not found any clavicle finite element models including implants. The inconsistency of the results in the literature is probably largely due to the differences in test modes [15].

The results show that this new method for modeling the stresses in conventional reconstruction plates placed on a clavicle bone, incorporating the loading muscle and ligament forces, is promising and shows plausible stresses and displacements. The two different models of the bone, namely the orphan-mesh one and the solid bone one show similar results. These results suggest that the mesh-based strategy can be swapped with the solid-body modeling strategy. The small deviation in the results regarding the displacement, (u=0,53 mm in solid and u=0,61mm in mesh)can be explained by the fact that in the mesh model there is a cavity representing the spongious part of the bone while in the solid model there is no such cavity. The impact of that difference has to be further investigated in future work.

To be able to optimize customized plates, models incorporating proper geometry, material and input forces are essential. Using the results of the comparison between the custom-fit and conventional reconstruction plates in the same loading situation, one can conclude that, in this particular case, the new customized plate can withstand at least the same loads as the conventional one.

It is also worth mentioning that the geometrical features of the customized plate are different to the conventional LCP plate, resulting in a narrower and thinner plate design, while allowing for the same loads as thicker, conventional fixation plates. The resulting maximum stress in the customized plate is still lower than in the LCP Reco plate, due to the absence of reconstruction segments and the cup-shaped design. Moreover, these preliminary results indicate that the method, with further work, can be used for the computer-based optimization of all the necessary parameters in the design of customized fixation plates for clavicle fractures. In further studies, the more commonly used, anatomically shaped plate will be included in the study and used in the comparison with the customized plates.

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