Original Article

Biomechanical analysis of titanium fixation plates and screws in mandibular angle fractures

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Abstract

Objective: The aim of this study was to evaluate the mechanical behavior of different rigid fixation methods in mandibular angle fractures.
Materials and Methods: Three different three-dimensional finite element models of the mandible were developed to simulate the biomechanical responses of titanium plates and screws. The fracture lines were fixed with double 4-hole straight, 4-hole square, and 5-hole Y plates with monocortical screws. 150 N incisal occlusal loads were simulated on the models. The commercial ANSYS software was utilized to calculate the Von Mises stresses on fixative appliances.
Results: The highest Von Mises stress values were observed in the Y plate, whereas the lowest stress values have been found in the square plate.
Conclusions: The use of square plate led to better stability and lower mechanical stresses than other techniques.

Key words: Bone plates, bone screws, finite element analysis, jaw fixation techniques, mandible, mandibular fractures

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Introduction

The mandibular angle is one of the most commonly fractured sites in the mandible.[1] The frequent involvement of the mandibular angle can be attributed to changes in the lines of calcification and strength from the horizontal body to the vertical ascending ramus, the thinner cross-sectional area, and the presence of impacted or partially erupted third molars.[2] Fractures of the mandibular angle are the most problematic in the facial region because of the high frequency of complications and difficult access to the surgical site.[3]

Traditional methods of mandibular angle fracture fixation included wire osteosynthesis and maxillomandibular fixation. These fractures are currently treated by plate/screw osteosynthesis and depending on the case, the bone segments are secured by one-miniplate fixation, two-miniplate fixation, or by a single rigid plate.[4] However, the discussion about the ideal type of fixation for mandibular angle fractures is still going on.

Fixation of mandibular angle fractures is biomechanically complex because the major stress-bearing of the mandible are disrupted in this area.[5] Finite element analysis (FEA)

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is a numerical analysis technique that can determine the displacements, stresses, and strains, over an irregular solid body given the complex material behavior and the loading conditions imposed upon that body. The stress analysis obtained from FEA modeling of the maxillofacial bony structures can provide information regarding interactions between hardware and bone during normal patient functioning.[3,6-10]

Previous studies have shown the utility of finite element modeling in capturing the unique and complex biomechanics of mandibular fracture deformation.[3,11-13] The aim of this study was to evaluate the biomechanical behavior of different rigid fixation systems in mandibular angle fractures by means of FEA.

Materials and Methods

A three-dimensional (3D) finite element model was constructed from the serial computed tomography (CT) scans of a dentate human mandible. Serial axial sections in every 0.5 mm of the mandible were obtained from a CT imaging system (Aquilion 64 Multi TSX-101A/4A; Toshiba Co., Tokyo, Japan). The images were restored using digital imaging and communications in medicine as a 3D medical image file format. The 3D image of the mandible was imported into Mimics software (version 12.1, Materialise, Ann Arbor, MI) for preprocessing and modeling.

In the absence of information concerning the precise organic material properties of bone, cortical and cancellous bone were assumed to be isotropic, homogeneous, and linearly elastic as were the other materials used in this analysis. The young modulus and Poisson ratios of materials used in the analysis are listed in Table 1.

A fracture was simulated by dividing the mandibular corpus with a plane at the angle of the mandible by using a 3D computer-aided design software SolidWorks (SolidWorks Japan, Tokyo, Japan). The fracture extended from just posterior to the typical location of the third molar to the most posterior inferior point on the angle.[3]

Three separate fixation scenarios were evaluated: (1) Double 4-hole straight miniplates with parallel standard plating, (2) a 5-hole Y plate, and (3) a 4-hole square plate. Therefore, three different FEA of surgical fixation methods were developed [Figure 1]. The computer model of the titanium miniplates were based on physical specimens of W. Lorenz (Walter Lorenz Surgical, Jacksonville, FL 32218, USA) 4-hole straight, 5-hole Y, and 4-hole square standard 2.00 mm miniplates, which feature a 1.00 profile. The fixative appliances were modeled with the aid of SolidWorks (SolidWorks Japan, Tokyo, Japan). Screws were modeled as simple 2.00 mm cylinders of length appropriate for monocortical penetration for the fixation of miniplates. Miniplates were considered to be in perfect contact with the cortical and spongious bone as well as the plate hole through which it was mounted. The plates were assumed not to receive or transmit any force directly from the bone segments.

In this study the basic loading conditions, namely biting with occlusal contact at the site of incisors,were investigated. A wide range of magnitudes for chewing forces has been reported in the literature. The magnitude of the vertical load in this study was set at 150 N. The condyle was fixed in all three directions to represent the reaction force at the temporomandibular joint.

The ANSYS finite element solver software (Version 14; ANSYS Inc., Canonsburg, PA) was used to calculate stresses in each model. The software used in this study could easily automesh the complicated mandibular model when the tetrahedron elements were utilized. The stress contours were computed and plotted in the bone tissue and in the fixation appliances. The screws were numbered consecutively from the top to the bottom.

Results

The von Mises stress values represent the beginning of deformation for ductile materials such as miniplates. Based

Table 1: Mechanical properties of bony structures and fixation materials in finite element analysis

	Young's modulus (ε), GPa	Poisson ratio (ν)
Cortical bone	14.8	0.30
Cancellous bone	1.85	0.30
Titanium alloy	113.8	0.342

Table 2: Highest von Mises stress values recorded on the models under incisal load

Model	von Mises stress (MPa)
Upper plate	615.94
1st screw	182.77
2nd screw	331.92
3rd screw	468.58
4th screw	252.35
Lower plate	645.37
1st screw	174.41
2nd screw	324.19
3rd screw	322.18
4th screw	186.88
Square plate	548.91
1st screw	447.35
2nd screw	456.15
3rd screw	469.61
4th screw	472. 16
Y plate	1444.2
1st screw	445.87
2nd screw	159.91
3rd screw	560.11
4th screw	178.19
5th screw	60.35

on the stability criteria defined by von Mises, if the maximum tensile stress for each structure (bone or screw) is exceeded, the structure may fail.[14] In this context, the von Mises stress values on fixative appliances were predicted by means of 3D FEA. The highest values of von Mises stress are shown in Table 2. A color scale with 9 stress values was used to assess quantitatively the stress distribution in the fixative

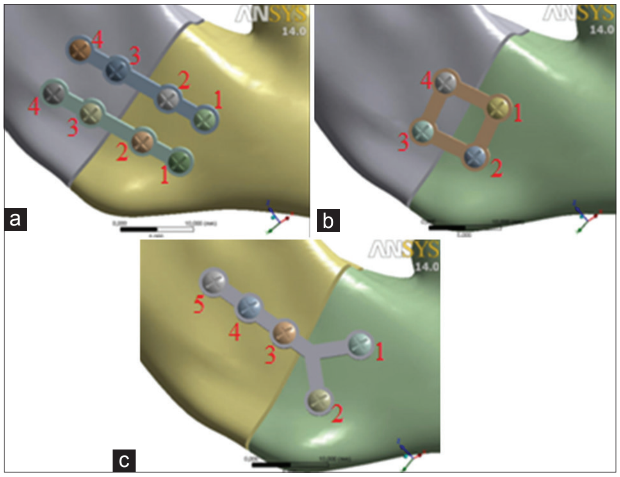

Figure 1: Three-dimensional finite element models: (a) Double straight plates; (b) square plate; (c) Y plate

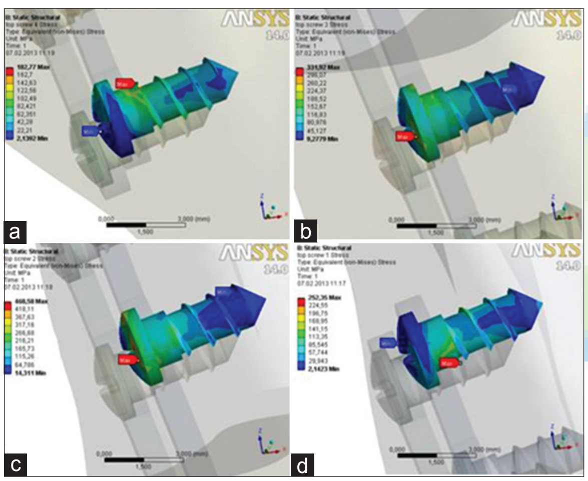

Figure 3: Three-dimensional von Mises stress distribution fields in screws of the upper plate: (a) 1st screw, (b) 2nd screw, (c) 3rd screw, and (d) 4th screw

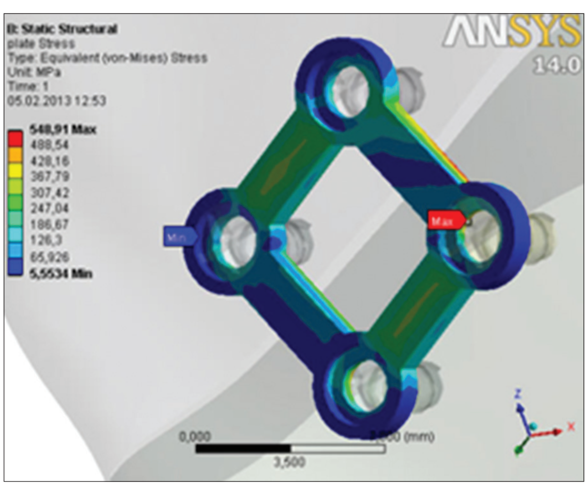

Figure 5: Three-dimensional von Mises stress distribution fields in the square plate

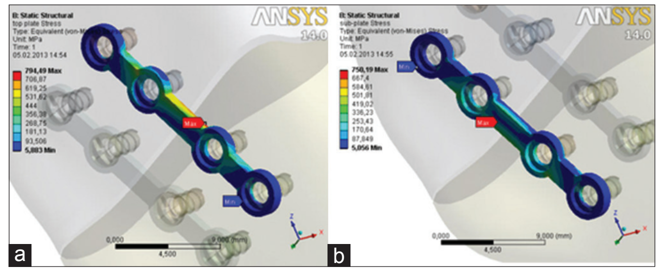

Figure 2: Three-dimensional von Mises stress distribution fields in (a) upper and (b) lower straight plate

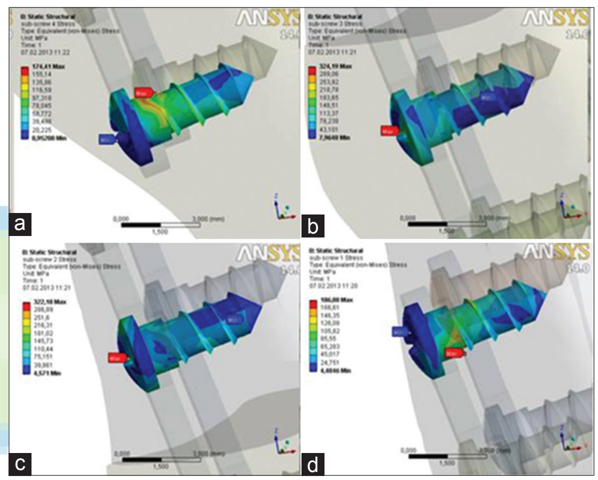

Figure 4: Three-dimensional von Mises stress distribution fields in screws of the lower plate: (a) 1st screw, (b) 2nd screw, (c) 3rd screw, and (d) 4th screw

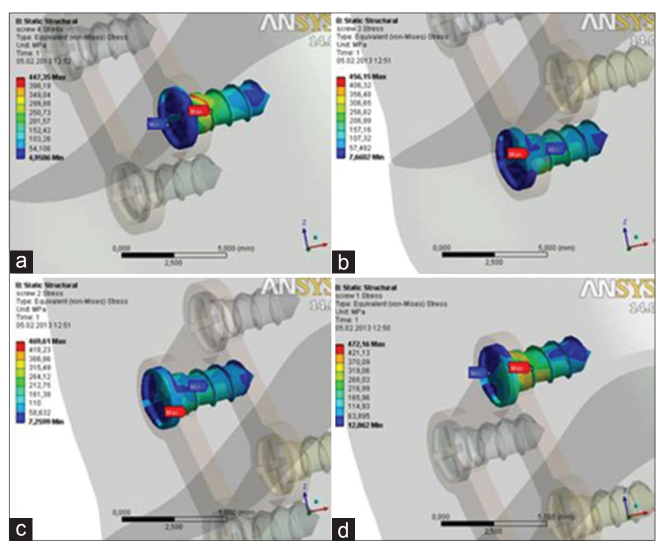

Figure 6: Three-dimensional von Mises stress distribution fields in screws of the square plate: (a) 1st screw (b) 2nd screw (c) 3rd screw (d) 4th screw

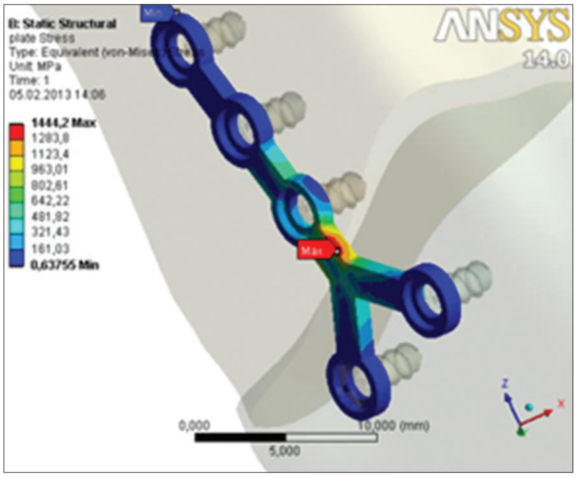

Figure 7: Three-dimensional von Mises stress distribution fields in the Y plate

appliances. 3D von Mises stress distribution fields in plates and screws have been shown in Figures 2-8. On comparing the three fixation techniques, the highest von Mises stress values were observed in the Y plate, whereas the lowest stress values have been found in the square plate. The evaluation of von Mises stress in fixation groups showed that the stress distribution was homogeneous in the square plate–screw complex.

Discussion

The Champy technique has been widely used by oral and maxillofacial surgeons in maxillofacial trauma. However, the debate as to the ideal miniplate fixation of mandibular angle fractures still exists. The relative ease of miniplate placement via intraoral approach, the small size of the plate, and adaptability are all reasons in support of this method. On the other hand, some disadvantages have been attributed to Champy's mandibular osteosynthesis, such as poor resistance to torsional forces, poor rigidity, and poor stability in angle fractures. Recently, the authors have turned their attention to new methods that will overcome these disadvantages.[2] These methods include 3D plates, lag screws, locking plate-screw systems, and double miniplate systems.

The miniplate osteosynthesis is a standard method for the surgical treatment of mandible fractures. In planning the stages of fracture treatment, the determination of best positioning and orientation and selection of plate type and material are important. The first criterion is the rigidity of the repaired fracture section and the second is the stress levels in miniplates under bite forces.[15] Therefore, in the present study, the biomechanical effects of three different type and configurations of miniplate osteosynthesis as applied to the 3D FEA of the mandible were analyzed. In this study,

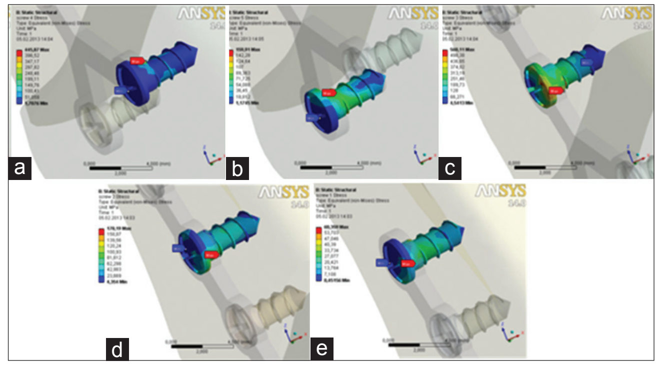

Figure 8: Three-dimensional von Mises stress distribution fields in screws of the Y plate: (a) 1st screw, (b) 2nd screw, (c) 3rd screw, (d) 4th screw, and (e) 5th screw

not only straight miniplates are considered, but also Y or square-shaped miniplates are considered by using FEA, which is not available in the literature. Therefore, the deformation and stress distribution of miniplates were investigated.

FEA is an analytical system widely applied in engineering and the aerospace industry and can also be used to solve complex problems in oral and maxillofacial sciences. In FEA method, the computational model is developed based on the modular principle and is made from many finite size elements; thus, it is well adapted to the real structures. The procedure is termed as discretization. Under some given conditions of clamping tension and stress, the deformations and strains of these simple elements can be calculated. Based on the linkage conditions of elements to nodes, the deformation of the overall structure at every node and the variables derived from this as well as the strains can be calculated.[9]

Several biomechanical studies that compared different forms of rigid internal fixation for mandibular angle fractures have been performed. Some studies have compared the differences between fixation systems by means of computer-based methods,[3,16] while some studies have used *in vitro* biomechanical tests.[2,15-18] Computer simulation models including FEA address the adequacy of mathematical models to relate mechanical factors such as load transfer to the biomechanical behavior of specimen. Given a high correlation between the FEA and the experiment, various data within the specimen can be visualized using the finite element calculation. The accuracy of FEA describing the biomechanical behavior of bony specimens has been shown by different authors.[19]

The rationale behind this study was to test the effectiveness of three different plating techniques and find the optimal method that would overcome the disadvantages of other plating techniques. Our results showed that the square plate provided more biomechanical stability than the other techniques. These results are in accordance with those of studies that have previously reported the placement of a 3D strut plate to have favorable biomechanical behavior.[20-22]

The square plate can be considered a two-plate system, with two miniplates joined by interconnecting crossbars, which is similar to 3D plates. Because the screws are arranged in the configuration of a box on both sides of the fracture, a broadband platform is created, increasing the resistance to twisting and bending to the long axis of the plate. One of the advantages of this technique is the simultaneous stabilization of the tension and compression zones, making these plates a time-saving alternative to conventional miniplates.[5]

The Y plate-screw system was subjected to higher stresses among other plate systems. This can be attributed to the design of the plate which prevents homogeneous load transfer along the plate and screws.

The use of two-miniplate fixation technique to treat mandibular angle fractures provides a better stability compared with Champy's method. The use of two miniplates avoids lateral displacement of the lower mandibular border and opening of the inferior fracture gap, which are suspected to contribute to the occurrence of complications. The two-miniplate technique has also some disadvantages. When using an intraoral approach, the two-miniplate fixation technique necessitates reflection of all soft tissues from the mandible, increasing intraoperative trauma. When using an extraoral approach to place the second miniplate on the inferior border, it increases the risk of bacterial contamination, scarring, postoperative edema, hematoma, and marginal mandibular nerve damage. The use of two-miniplate fixation also prolongs the operation time and increases the financial costs as well.[5]

Although 3D FEA illustrates stress behavior more realistically than the other methods in considering the complexities that characterize actual clinical conditions, there are some limitations. In the current study, several assumptions and simplifications have been made with regard to the material properties. For example, bone is anisotropic. However, in FEA models, bone is frequently modeled as isotropic. The structures in the models were all assumed to be homogenous, isotropic, and linearly elastic.[10]

Conclusion

Our findings demonstrate that the square plate and screw system offers more resistance and stability to the occlusal displacing forces at the fracture site than other techniques used in the current study. This plate design can be used successfully in the treatment of noncomminuted mandibular angle fractures.

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Conflicts of interest
There are no conflicts of interest.

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