Original Article

Biomechanical analysis of titanium fixation plates and screws in sagittal split ramus osteotomies

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Abstract

Objective: The aim of the study was to evaluate the mechanical behavior of three different fixation methods used in the bilateral sagittal split ramus osteotomy.

Materials and Methods: Three different three-dimensional finite element models were created, each corresponding to three different fixation methods. The mandibles were fixed with double straight 4-hole, square 4-hole, and 5-hole Y plates. 150 N incisal occlusal loads were simulated on the distal segments. ANSYS software ((v 10; ANSYS Inc., Canonsburg, PA) was used to calculate the Von Mises stresses on fixative appliances.

Results: The highest Von Mises stress values were found in Y plate. The lowest values were isolated in double straight plate group.

Conclusions: It was concluded that the use of double 4-hole straight plates provided the sufficient stability on the osteotomy site when compared with the other rigid fixation methods used in this study.

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

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Introduction

The bilateral sagittal split ramus osteotomy (BSSRO) as described by Obwegeser and Dal-Pont is now a standard, common and successful procedure in oral and maxillofacial surgery for the treatment of certain mandibular discrepancies.[1,2] Miniplates and screws are used to achieve fast bone healing, to avoid postoperative intermaxillary fixation, and to initiate early postoperative mandibular function and oral hygiene. Postoperative skeletal stability is also improved.[1-5]

To better understand the biomechanics of sagittal split ramus osteotomy and to assess different rigid internal fixation methods using titanium miniplates and screws we used three-dimensional (3D) finite element analysis (FEA) to measure the stress in the fixative appliances. Baiamonte *et al*. compared *in vitro* measurements of the strain on loaded mandibles that had osseointegrated titanium implants with those obtained by the FEA.[6] The measurements were in close agreement and the authors concluded that FEA is applicable to dental systems. The method allows virtual reality modeling of the mandible, fixation plates, and screws. It requires exact knowledge of the material variables as well as the geometry of the mandible and the fixation materials under investigation.[1]

The aim of the study was to compare three methods of rigid fixation with their different designs after setback sagittal split ramus osteotomy and evaluate the complex biomechanical behavior under posterior loading forces, using 3D FEA.

Materials and Methods

A 3D virtual model of the mandible was constructed from the serial computed tomography (CT) scans of a human

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dentate mandible using 3D DICOM data with 0.5 mm thickness cut. Serial axial sections of the mandible were obtained from a CT imaging system (Aquillion 64 Multi TSX-101A/4A; Toshiba Co., Tokyo, Japan). The images were restored using DICOM as a 3D medical image file format. The 3D image of the mandible was imported into MIMICS software (v 12.1, Materialise, Ann Arbor, MI, USA) for preprocessing and modeling.

In the absence of information about the precise organic properties of bone, cortical, and cancellous bone structures were assumed to be isotropic, homogenous, and linearly elastic. The young modulus and poisson ratios of materials used in the analysis are listed in Table 1.

The BSSRO was simulated on the models by means of 3D computer aided design software SolidWorks (SolidWorks Japan, Tokyo, Japan). The two bone fragments were tightly fixed together after the bone was cut, therefore only allowing the displacement in the direction of the chewing force.

Three different rigid fixation methods-double straight plates, square plate, and Y plate-were compared in this study. Thus, three different FEA meshes of surgical fixation methods were then developed for the osteotomy site fixation [Figure 1]. The computer model of the titanium miniplates were based on a physical specimen of a W. Lorenz (Walter Lorenz Surgical; Jacksonville, 32218 FL, USA). 4-hole straight, 5-hole Y, and 4-hole square plates were modeled separately. Screws were modeled as simple 2.00 mm cylinders of length appropriate for monocortical penetration for the fixation of miniplates. The fixation appliances were simulated by using the 3D computer aided design software SolidWorks (SolidWorks Japan, Tokyo, Japan). Each miniplate was determined to be in perfect contact with the cortical and spongious bone surrounding it as well as the plate hole through which it was mounted. It was assumed that the plates did not receive or transmit any force directly from the bone segments.

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

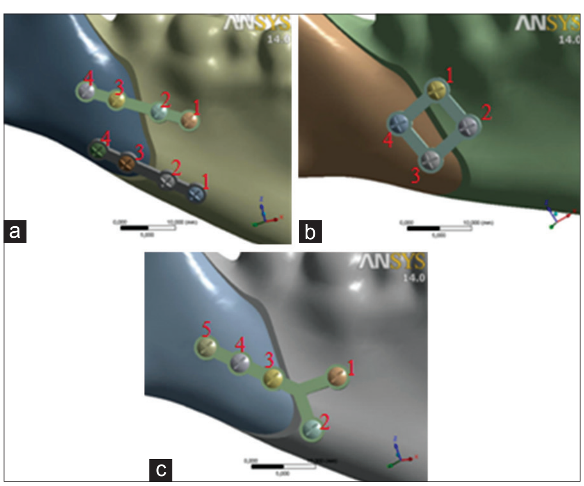

Figure 1: Three-dimensional finite element models: (a) Double straight plates, (b) Square plate, (c) Y plate

A range of magnitudes of chewing forces has been reported.[7-9] We set the magnitude of incisal occlusal load at 150 N. This load was applied to the incisal edge of central incisor teeth. Loading forces on the models were all static. The condyle was fixed in all three directions to represent the reaction force at the temporomandibular joint.

The ANSYS finite element solver software (v 14; ANSYS Inc., Canonsburg, PA) was used to compute the stresses in each mandibular model. Stress contours were computed and plotted in the bone tissue and in the fixation appliances. The screws were numbered as seen in [Figure 1a-c.]

Results

The von Mises stress in the fixation appliances is predicted by FEA. The stability of a 3D state of stress is evaluated according to the stress hypothesis by Von Mises. If the maximum tensile stress for each structure is exceeded, the structure may fail.[10] A color scale with nine stress values served to evaluate quantitatively the stress distribution in the fixation appliances. 3D Von Mises stress distribution fields in plates and screws have been shown in [Figures 2-8]. The highest Von Mises stress values have been isolated in Y plate group, whereas the lowest values were detected in double straight plate group, especially for the upper plate. The stress distribution was homogenous in the screws of the square plate system. Table 2 shows the maximum stress distribution in each group.

Discussion

Several biomechanical studies have been conducted that compared different forms of rigid internal fixation. A wide variety of these studies have compared the differences

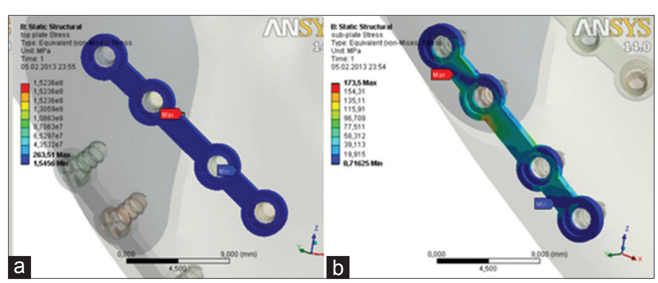

Figure 2: Three-dimensional Von Mises stress distribution fields in (a) upper and (b) lower straight plates

between fixation systems by using biomechanical tests,[11-15] while some have used FEA.[1,2,10,16-19] FEA provides a close approximation of the *in vivo* geometry, which includes the modeled section of the mandible, the mechanical properties of the mandible, and the selected fixative appliances.[20]

In the present study, three different rigid fixation methods were chosen to undertake a comparison with each other. A 3D FEA was selected to evaluate the complex mechanical behavior under incisal occlusal load. The test load was applied down on the incisors because that showed more effect on the osteotomy site than torsional loading on molars.[21]

Finite element analysis is a numerical method for addressing biomechanical questions and is a powerful research tool that can provide precise insight into the complex mechanical behavior of the mandible affected by mechanical loading, which is difficult to assess otherwise.[11] Consequently, 3D FEA allows for a more realistic representation of stress distribution than would be the case with a two-dimensional simulation.[10] In FEA, by means of a process called discretization, a mathematical model is built up, in similar way to building block construction, from a number of finite elements. It is therefore well adapted to the actual structure. Under given conditions of constraint and loading, the deformations, and stresses of these simple elements may be calculated. The elements are connected to each other by nodes. The deformation and the measurement, including strains, derived for the whole structure can be calculated at each node, through the connection conditions of the elements at the nodes.[22]

Finite element analysis has inherent limitations. The values of the stresses provided by FEA are not necessarily identical to actual ones.[1,2] In the current study, several assumptions and simplifications have been made regarding the material properties and model generation. In FEA models, bone is frequently modeled as isotropic, whereas it is anisotropic.

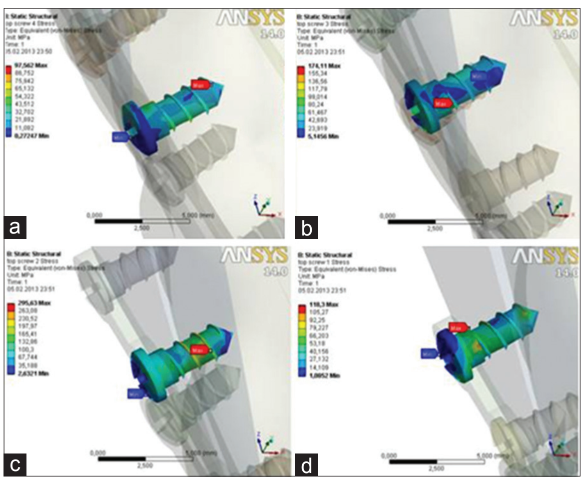

Figure 3: Three-dimensional Von Mises stress distribution fields in screws of upper plate, (a) 1st screw, (b) 2nd screw, (c) 3rd screw, (d) 4th screw

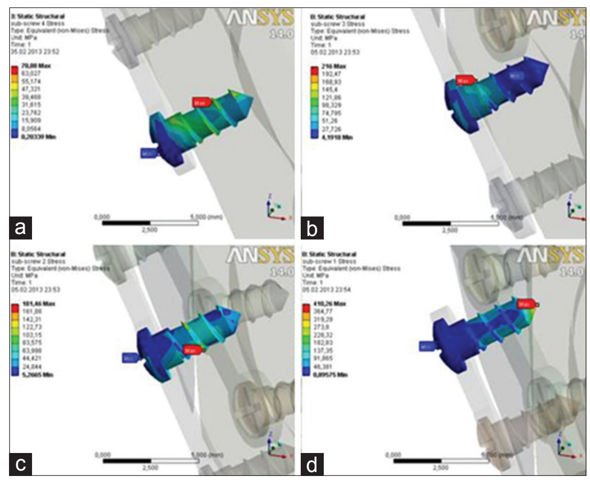

Figure 4: Three-dimensional Von Mises stress distribution fields in screws of lower plate, (a) 1st screw, (b) 2nd screw, (c) 3rd screw. (d) 4th screw

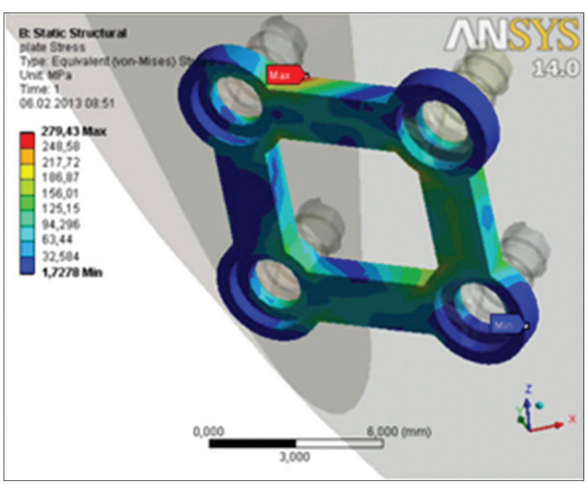

Figure 5: Three-dimensional Von Mises stress distribution fields in square plate

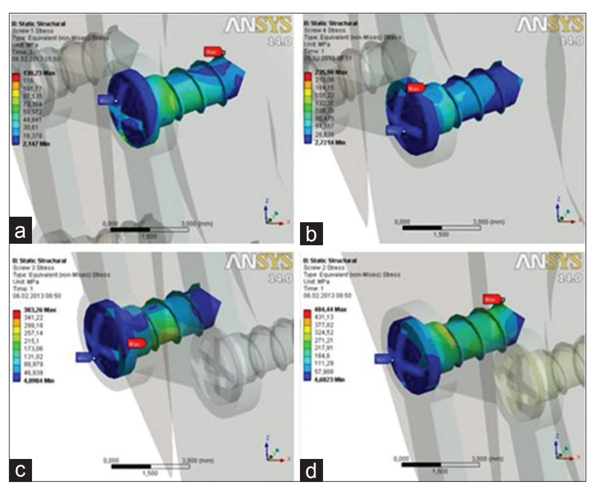

Figure 6: Three-dimensional Von Mises stress distribution fields in screws of square plate, (a) 1st screw, (b) 2nd screw, (c) 3rd screw, (d) 4th screw

The properties of the materials modeled in the study, particularly the living tissues, are different, for example cortical bone is transversely isotropic and inhomogeneous, but the structures in the model were all assumed to be homogenous, isotropic, and linear elastic.

Rigid fixation stability on fractured bone increases with the buttressing effect of fractured segments. Osteotomy lines in orthognathic surgery often do not have this effect, and it is difficult to compare the stability results of rigid fixation of fractured bone with fixation in BSSRO. Nevertheless, the desirable configuration of rigid fixation methods can be compared to assess and prevent the excessive stress around fixation appliances that may cause failure.[17]

In our study, double parallel miniplates led to better stability and lower mechanical stresses compared to Y and square plate fixation. Compared with the lower plate, the upper plate showed greater stress values as a result of bearing tension forces. Square plate fixation provided a homogenous load transfer among screws. Double parallel plate fixation provided greater resistance to the simulated functional forces than the two other techniques. The Von Mises stress values were the highest in Y plate and screw complex. This can be attributed to the geometry of the plate which prevents a uniform load transfer along plates and screws.

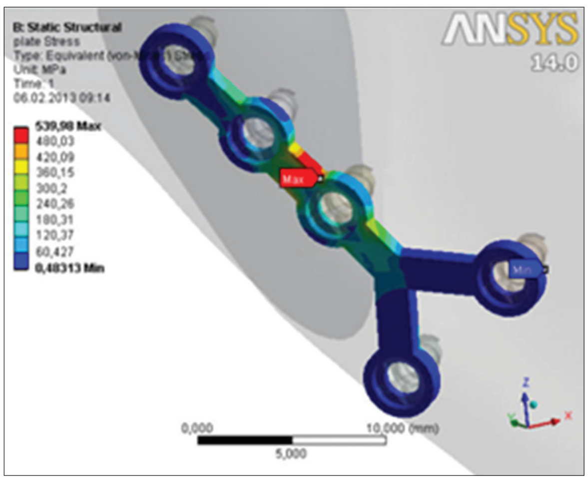

Figure 7: Three-dimensional Von Mises stress distribution fields in Y plate

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

Model	Von Mises stress (MPa)
Upper plate	263.51
1st screw	92.56
2nd screw	174.11
3rd screw	205.63
4th screw	118.3
Lower plate	173.5
1st screw	70.88
2nd screw	216
3rd screw	181.46
4th screw	410.26
Square plate	267.63
1st screw	118.83
2nd screw	230.18
3rd screw	413.36
4th screw	498.34
Y-plate	539.98
1st screw	155.42
2nd screw	119.18
3rd screw	354.17
4th screw	1053.8
5th screw	84.25

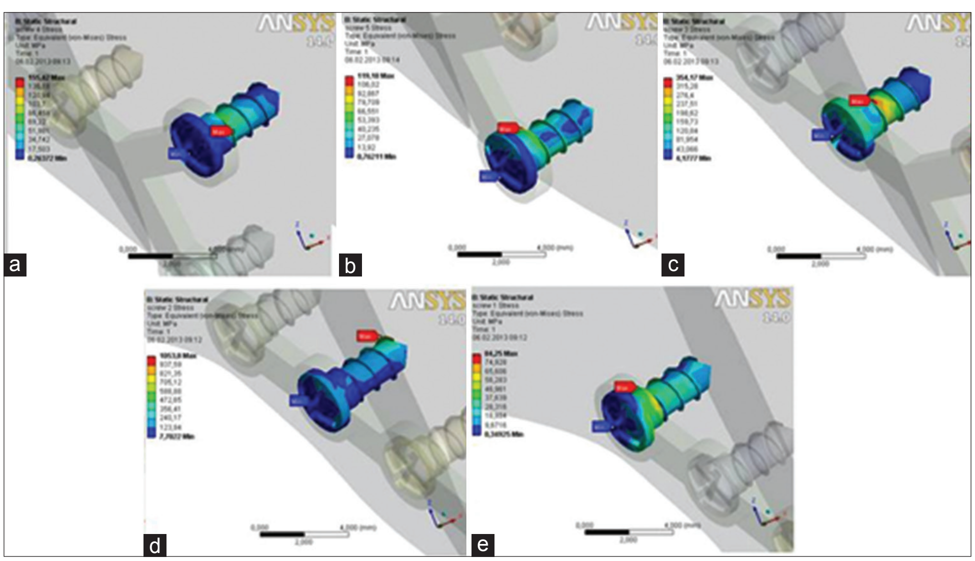

Figure 8: Three-dimensional Von Mises stress distribution fields in screws of Y plate, (a) 1st screw, (b) 2nd screw, (c) 3rd screw, (d) 4th screw, (e) 5th screw

Tams *et al*. concluded that for angle fractures the most important function of a second plate is not to resist the negative bending movements but to help the upper plate resist the high positive bending movements.[23] In light of this knowledge, the second plate is most effective in reducing the mobility of fractures and osteotomies. We found that Von Mises stresses were reduced in double plate method, which is why we used double miniplates with monocortical screws to stabilize the osteotomy resulting in greater biomechanical stability.

There is a consensus in the literature that the technique of applying a miniplate with monocortical screws for SSRO fixation presents inferior mechanical resistance compared with the bicortical screw technique. Clinically, the miniplate resistance is enough to promote bony healing during the postoperative period, as bite forces in the acute phase of postoperative period are much weaker than those registered for the rest of the postoperative period or the nonoperated population. This lower mechanical resistance is due to inferior bone contact in the osteotomy region compared with the use of bicortical screws, as well as the fact that the miniplate receives the greater part of the masticatory load with great stress concentration around the screws in areas of little bone thickness.[11] However, the miniplate fixation shows advantages, such as granting intraoral route, minimal torsion on the condyle, and less risk of inferior alveolar nerve injury. It is particularly advantageous in larger advancements where proximal and distal overlap is minimal. For many surgeons, the straight type of miniplates with monocortical screws is a popular choice.[21]

The mechanical results of our study confirm that the use of double straight plate technique has a higher and more sufficient mechanical stability, when compared with the square and Y plates. The use of this technique is also associated with lower Von Mises bone stress on fixation appliances.

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