Original Article - In-Vitro Study

Finite Element Analysis of New Modified Three-dimensional Strut Miniplate versus Conventional Plating in Mandibular Symphysis and Angle Fractures - An *In vitro* Study

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Abstract

Introduction: Mandibular fractures are common injuries during maxillofacial trauma, and currently, open reduction and internal fixation are considered gold-standard treatments. There is a wide discussion about which plates give the best outcomes. Hence, we are conducting a biomechanical comparison of two plates for mandibular symphysis and angle fracture with finite element analysis (FEA). The aim of this study was to do a comparative study of FEA between the conventional and our new modified three-dimensional (3D) strut miniplate in mandibular fractures at symphysis and angle regions. **Materials and Methods:** Finite element models of symphyseal and angle fractures of the mandible were developed. Each fracture model was then realigned and fixed by the conventional method 2.0 mm system, and our modified 3D strut plating method 2.0 mm system followed by the analysis of various stresses developed in plates and mandibular fracture area after application of load was observed in the study. **Results:** The modified 3D strut plating system with 2.0 mm miniplates is significantly better in preventing displacement of fracture segments by better distribution of forces compared to the conventional plating system. Rest of the parameters were within the permitted limits. **Discussion:** Modified 3D strut plating method was reasonably effective and superior in managing force-displacement compared to the conventional method of fixation for comminuted and unfavourable mandibular symphyseal fracture and angle fracture.

Keywords: Displacement of fracture, finite element analysis, mandibular angle fracture, mandibular symphysis fracture, Von Mises stresses

Introduction

The ability of any individual to masticate without pain, discomfort or interference is considered normal mastication. The normalcy of masticatory function can be determined by major determinants such as range of mandibular motion, occlusion, maximum occlusal forces and activity of primary and accessory muscles of mastication. Hence, when an individual has a traumatic or pathologic injury to the jaws, this function is grossly affected. Among all fractures of the maxillofacial region, mandibular fractures are the second most common in road traffic accidents.[1] Mandible fractures will lead to changes in the skeletal and dental configuration as well as in normal components of the masticatory system.

Mandibular fractures are complex fractures to treat due to various factors such as muscles of mastication, inferior alveolar nerve, occlusion and post-operative care.[2,3] Moreover, fractures of the mandibular angle are most problematic because of the high frequency of complications. Infection and non-union are common complications after open reduction and internal fixation.[4] The primary aim in the management of mandibular fractures is not only to restore their form but also their function and stability during the healing phase. This stability after treatment of a mandibular fracture mainly depends on forces generated by muscles of mastication as they act in different directions.[5] The current concepts for the management of mandibular fractures include different fixation systems, based on Champy's guidelines[6] of miniplate fixation. Different plating

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systems that are used include microplates, miniplates, locking miniplates, reconstruction plates, three-dimensional (3D) plates, titanium hollow screw reconstruction plates and compression plates.[7] Based on Champy's ideal line of osteosynthesis, the conventional method uses two miniplates that are fixed between the mental foraminal region for symphysis fracture and two miniplate fixations, one superior miniplate adapted just below the external oblique ridge and another miniplate adapted near the inferior border of the mandible for angle fractures. According to Ellis, a single miniplate at the external oblique ridge is enough to provide rigid fixation for non-comminuted favourable angle fractures.[8] However, finite element analysis (FEA) by Ayali and Erkmen stated two plate fixations for angle, both at the superior and inferior borders give better stability than a single miniplate at any location for comminuted and displaced unfavourable angle fractures. Thus, single miniplate fixation can lead to flaring at the inferior border of the mandible and two plates prevent displacement of fracture and better stress distribution.[9]

Occlusal forces (bite force) are forces generated by the net result of different components such as muscles of mastication, bones and teeth. They are indicators of the functional state of the stomatognathic system, and the maximum load developed on teeth is the maximum bite force,[10] and this is considered a useful tool to assess the pre and post-operative functional state of the stomatognathic system and can be considered a major factor in the assessment of success in the treatment of mandibular fractures.[11] In this study, we believe that the application of our modified 3D strut plate at the symphysis and angle will allow increased resistance to vertical bite forces and will constrict motion in horizontal as well as vertical planes. Thus, it provides better stability on the lateral surface and prevents rotational forces of the mandible when compared to conventional miniplates. Better stability at the fracture site will allow better loading and functional use of the jaw during the healing phase without any unfavourable outcomes. Hence, it will let the patient use the jaw more comfortably during the healing phase, which will add more strength to the fractured mandible; hence, the fractured bone can be loaded with more pressure and more bite force can be generated without increasing micromovements at the fracture site during mastication, leading to better patient compliance. The aim of the study was to do a comparative study of FEA between the conventional and our new modified 3D strut miniplate in mandibular fractures at symphysis and angle regions.

Materials and Methods

A 3D scanner is used to develop a point cloud for the adult mandible model. The point cloud was later imported into SolidWorks, after which the model surfaced to develop the solid model. The STEP format of our solid model was exported to Meshmixer (Autodesk). From there, it was imported to Autodesk Simulation Mechanical for FEA [Figure 1]. The human mandible consists of a cortical bone rim, a cancellous part and teeth, which are formed by enamel, dentin and cementum. For this study, teeth have been excluded from the analysis and only bone is considered. All materials are modelled as elastic and isotropic, with elastic modulus (E) = 13,700 MPa and Poisson's ratio (V) = 0.3 for the cortical bone and elastic modulus (E) = 7930 MPa and Poisson's ratio (V) = 0.3 for the cancellous bone with an ultimate strength of 92 MPa. The plates used for the fixation of mandibular fractures were modelled in SolidWorks. Dimensions of the plates were obtained from the commercially available miniplates and our modified 3D strut plate [Figure 2] with the help of a profile projector (MP320). Two different fixation points of mandibular fractures were investigated in the present study. Conventionally, two miniplates were positioned for symphysis and two miniplates, one slightly under the external oblique ridge and another along the lower border for angle fracture, while in our modified 3D strut plate, a single plate was placed for both symphysis and angle fractures. The plates and screws were made of titanium, with an elastic modulus (E) of 116,000 MPa and Poisson's ratio (V) of 0.34, the tensile strength of 345 MPa, yield strength of 275 MPa and elongation at break of 20%. Screws were simulated as solid cylinders with a diameter of 2.0 mm (similar to the major diameter of actual screws).

A line-split tool in SolidWorks was used to fracture the solid mandible at symphysis and angle regions. The split parts were later given surface contacts with the fixation plates for FEA. Within the Autodesk Inventor assembly environment, the plates were added to the fracture assembly at desired locations. This assembly is then imported into the computer-aided engineering environment in Autodesk Simulation Mechanical for finite element (FE) modelling. The mandible and plates were meshed with tetrahedral elements with a respective mesh size. Pin constraints were set up to allow hinging action around the ends of the mandible, and as all teeth have different responses to forces applied, teeth surfaces were made fixed in the FEA model for mandibular symphysis fracture and mandibular angle fracture; thus, they will act as a mode of force transfer [Figure 3]. As teeth are fixed in this study, forces absorbed by periodontal ligament (PDL) were not considered. According to Fongsamootr *et al*.,[12] PDL have a significant role in absorbing forces during mastication. The masticating force lies in the range of 100–600 N. For the present study, FEA was performed using loads of

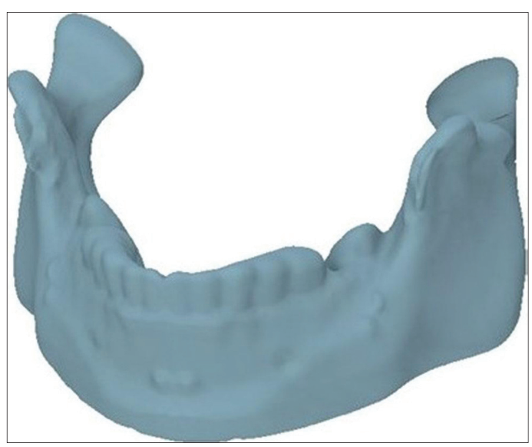

Figure 1: STEP file of human mandible

157.9 N and 503.2 N provided at the incisor and molar regions, respectively, to mimic the biting action. As teeth are fixed for both methods of fixation, effect of PDL can be omitted. The load was given from the lower side of the mandible in the molar and premolar regions [Figure 4]. Plates, screws and mandible were given surface contacts between them.

Two different plating systems were analysed in the current study: conventional miniplates and our modified 3D strut plating system. The configurations of miniplates used for the fracture site were checked for their efficacy. In the group of conventional plate configuration, a) For symphysis two miniplates were placed on the lateral surface of mandible with a minimum gap of 2 mm between the two plates and b) For angle two miniplates are placed one slightly under the external oblique ridge and another along the lower border of mandible. In the group of 3D strut plate for both symphysis and angle plate placed in middle of lateral surface of mandible.

Figure 2: Our designed modified 3D strut plate

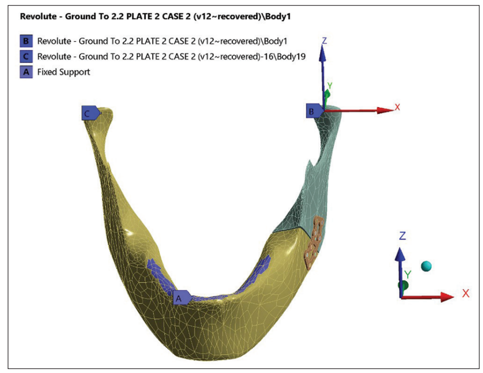

Figure 3: Shows which points are allowed rotating movements i.e., point B and C and which area was fixed for force transfer i.e., point A

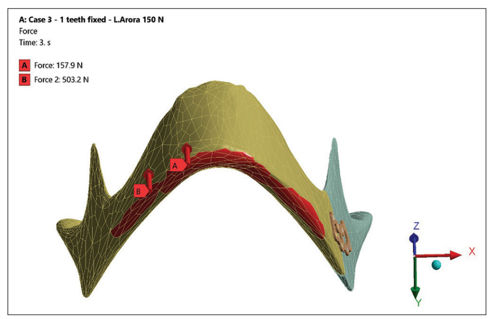

Figure 4: Shows area of loads in finite element models for studying the effect of loading in mandibular fractures

Results

The displacement of the mandible in conventional and our modified 3D strut plate is shown in Figure 5. The displacement at the symphysis region in conventional was 0.01048 mm, and in the 3D plate was 0.003 mm, almost 3.5 times less. The displacement at the angle region in conventional was 0.04102 mm, and in the 3D plate was 0.0061 mm, which is 6.7 times less. For the conventional plate, von Mises stresses at symphysis were 22.60 MPa, and for the 3D plate, they were 1.5 MPa and at angle was 1.2 MPa [Figure 6]. The overall stress generated in the plate and screw assembly at the symphysis region was 13.32 MPa in conventional plates and 5.2 MPa in 3D strut plates, and at the angle region was 184.11 MPa in conventional plates and 1.6 MPa in 3D strut plates. In all the parameters, the P-value ($T \leq t$) is < 0.001, thus suggesting statistical significance [Table 1].

Table 1: Max stress and displacement measures comparison

Measurement criteria	Conventional	3D strut plate	P ($T \leq t$)
Mean displacement (Symphysis)	0.01048 mm	0.003 mm	<0.001
Mean displacement (Angle)	0.04102 mm	0.0061 mm	<0.001
Mean von Mises stresses (Symphysis)	22.6 MPa	1.5 MPa	<0.001
Mean von Mises stresses (Angle)	25.8 MPa	1.2 MPa	<0.001
Mean overall stress (Symphysis)	13.32 MPa	5.2 MPa	<0.001
Mean overall stress (Angle)	184.11 MPa	1.6 MPa	<0.001

Discussion

According to various studies, the mandible is one of the most commonly affected bones during maxillofacial fractures around 36%–70%.[13] The primary aim in the treatment of mandibular fractures is to anatomically reduce the displaced bone fragments either by closed or open reduction and to stabilise the fractured segment by intermaxillary fixation (IMF) or internal fixation until osseous union takes place without any complications.[5] Charnley proposed that when bony fragments are placed under compression, it actually stimulates osteogenesis.[14] The healing of the fracture gap is directly correlated with the fracture gap width. Impairments such as poor mastication, temporomandibular joint dysfunction or chronic pain can occur if occlusion is not achieved. With recent advancements, successful treatment is favoured by factors such as a better understanding of biomechanical principles, easy availability of materials and improved surgical techniques. This approach will also provide a rapid return of functions at the psychological level.[15] The main disadvantage with conventional plating is to perfectly adapt the plate to the underlying bone to prevent malocclusion caused by alterations in the alignment of fractured segments as screws are tightened can cause decreased primary stability.[16] Repeated bending during the adaptation of

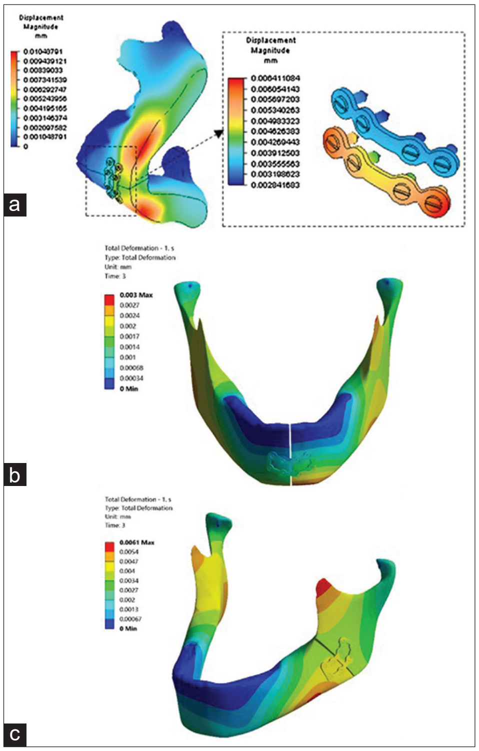

Figure 5: Displacement of the mandible in conventional and modified three-dimensional (3D) fixation method (in mm). (a) Conventional plating at the symphysis of the mandible, (b) Modified 3D plating at the symphysis of the mandible, (c) Modified 3D plating at the angle of the mandible

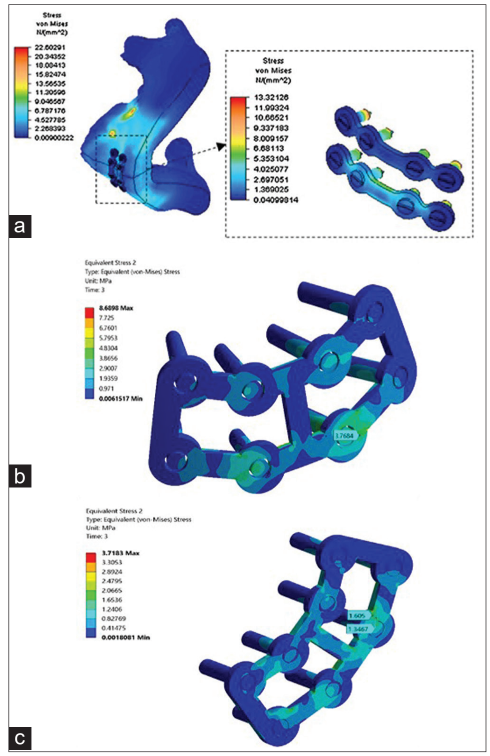

Figure 6: Von Mises stresses generated mandible using conventional and modified three-dimensional (3D) fixation method (in MPa). (a) Conventional plating at the symphysis of the mandible, (b) Modified 3D plating at the symphysis of the mandible, (c) Modified 3D plating at the angle of the mandible

plates may cause excessive strain and create pre-determined breaking points.[17] Theoretical advantages of 3D plates include precise plate adaptation, less displacement of bone on screw tightening and greater stability.[18] During the healing process, micromotions occurring at the fracture site due to frequent masticatory loads during function will cause interference and lead to non-union at the fracture site, the rate of which has been reported to be 3.7%.[3,19] Many factors are known to cause non-union, out of which inadequate stabilisation or reduction is the most important.[4] According to Pradeep *et al*., 1-week IMF postoperatively will decrease the micromovements and increase stability, thus improving the healing.[20] Based on our results, we suggest that no post-operative IMF is required as there are almost five times fewer micromovements compared to conventional miniplates, and the vertical bars will also provide more stability in function by preventing torsional forces during the healing phase. Therefore, the aim of our study is to compare the most effective fixation method to stabilise the fracture, which results in less mechanical stress on the mandible.

During treatment planning, the determination of position, orientation, type of plates and material of plates are of significant importance. The two criteria used are, first the rigidity of the repaired fracture section, and second, the stress levels that are developed in the miniplates when subjected to bite force.[11] Vollmer *et al*., and Korioth *et al*., studied the physical behaviour of human mandible deformation under an experimental setting and compared it with results derived from FEA. They concluded that the FE model is a valid and accurate, non-invasive method to predict different parameters of the complex biomechanical behaviour of the human mandible.[21,22] Sadhwani and Anchlia evaluated conventional and 3D plate models and found less stress around screw holes of 3D miniplate comparatively.[23] The FEA results of their study suggest that 3D miniplate fixation is more suitable for fixing mandibular symphysis fractures. The maximum permissible displacement to allow proper healing at the fracture site should be <150 μm.[24,25] Furthermore, loads transmitted through plates during function should not exceed the strength limit of the material.[26,27] In our study, the maximum interfragmentary displacement was <0.003 mm in our modified 3D plating system at symphysis and 0.0061 mm at angle. It is within the permissible limit for uncompromised bone healing. However, as our 3D plate has five times less displacement, it will give more stability while healing, and thus, the patient can return to early function. According to a study, the ultimate stress for cortical bone in tensile testing ranges from 92 to 188 MPa,[28] depending on the bone density of the subject. In our 3D plate, stresses generated were far below range at symphysis 1.5 MPa, and at angle 1.2 MPa. The static yield limit for titanium is approximately 1000 MPa.[29] Overall stress developed in the plate–screw assembly was 5.2 MPa at symphysis and 1.6 MPa at angle. It is of significance that loads transmitted through plates during the healing phase should never exceed the limit of tensile strength of the material. According to Ahmed *et al*.,[30] a load of around 752 N leads to permanent deformation in miniplates. The fixation device used in symphyseal fractures and angle fractures was quite effective in both groups. In our study, stress analysis revealed that maximal von Mises stress values were much lower than titanium yield stress indicating that the use of our modified 3D plate would be safe. The complex structure of the mandible cannot be mimicked by biomechanical models. However, these mathematical models give us an idea of different forces acting at the fracture site. Hence, it gives an indication for further clinical research to establish the exact condition in the clinical situation.

Conclusions

This study concludes that despite both 3D plate proposed by the authors and conventional miniplate functions on similar principles of load sharing mechanism, it is able to indicate that our modified 3D miniplate fixation is able to provide better resistance and stability to displacing forces in all the directions. The limitation of the procedure is the extraoral approach needed to perform fixation for angle fractures. Furthermore, the hardware is a little bulkier, but comparatively, the surface area is not much different than conventional miniplates. Any existing laceration or transbuccal approach can be used for fixation of angle fractures while symphysis fractures can be managed both intraorally or extraorally. Our 3D plate is not indicated in cases of parasymphysis fractures as the posterior vertical bar will encroach on the mental neurovascular bundle. We believe more clinical studies are to be performed to verify their exact role in fracture management. Thus, it can be stated that modified 3D plating seems to be as effective as conventional plating in the management of mandibular symphysis and angle fractures.

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Conflicts of interest

There are no conflicts of interest.

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