Comparative Evaluation of Efficacy of Twin Fork Shaped Miniplate Versus 3-Dimensional Miniplate for Fracture Fixation in the Transition Zone of Parasymphysis-Body Region Using Finite Element Analysis

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Abstract: ***The purpose of this study was to compare the biomechanical behavior of the twin-fork−shaped miniplate with the 3 dimensional miniplate for fracture fixationin the parasymphysis-body region using finite element analysis. The study was conducted on three-dimensional finite element computer model generated from measurements of a human cadaveric model of the mandible. In GROUP I, the twin fork miniplate was used, whereas fractures in GROUP II were fixed using conventional three-dimensional (3D) miniplate. The models were assessed for structural deformation and von Mises stress which was found to be lower for the twin fork miniplate than the 3D miniplate.***

Keywords: twin-fork miniplate; transition zone; finite element analysis; biomechanical evaluation; miniplate

1. Introduction

Fractures of the mandible in the region of the parasymphysis extending obliquely and traversing through the transitional zone to body area constitute almost 9% to 57% of all mandibular fractures. Anatomically, the presence of deeper roots of the premolar teeth, neurovascular bundle associated with the mental foramen and a change in density and orientation of the bony trabeculae makes mandibular parasymphysis-body fractures particularly problematic for the surgeons. The presence of mental neurovascular bundle gives rise to additional complications during reduction and fixation of the fracture segments in this zone**,** if manipulated too much during the procedure.1The mandibular parasymphysis and body regions are highly dynamic areas, constantly subjected to various types of muscular and occlusal force.[2]

It has been seen that the mandible is subjected to tension forces on its superior border and compression forces on its inferior border. The anatomy of the mandible and vector of forces exhibited by the masseter and temporalis muscles makes fractures in this region problematic. In the era before rigid internal fixation, this concept was known as the favorability or unfavorability of the fracture to be managed by closed reduction techniques and then to be secured by maxillo-mandibular fixation.[3, 4]

Fractures in the transition zone of the parasymphysis and body region represent a special pattern that creates a dilemma for the surgeons — whether to use one miniplate fixation or two miniplates, as suggestedby Champy.[2] Hence, twin fork shaped was created[1] with the aim of resolving this dilemma and additionally reducing damage to the neurovascular bundle. This design promises to follow Champy’s lines of osteosynthesis, and provides better stability and fixation compared to the conventional design.2 In addition, as a single modified miniplate is used instead of two plates, therefore it is also economically feasible for the patient, and reduces the risk of infection and wound dehiscence.[1]

Since there are limited Finite element analysis studies available with respect to this twin fork shaped miniplate on fixation of mandibular parasymphysis-body fractures, and no literature rendering details of comparison of this plate with the conventional 3D miniplate to the best of our knowledge, we aimed to conduct this study to compare the biomechanical behavior of this newly designed twin-fork−shaped miniplate with the 3-dimensional miniplate for the fixation of fractures involving the transition zone of parasymphysis and body region using finite element analysis.

2. Methodology

The fracture site in the transition zone of the parasymphysis–body region was determined and models were randomly assigned to two groups.

Group I-the twin fork miniplate with nine holes and an internal diameter of 2.25 mm and nine 2X8 mm screws were used

Group II-conventional 4 hole 3D miniplate with gap and with an internal diameter of 2.25 mm and eight 2X8 mm screws were used
Inclusion criterion was 3-dimensional finite element computer model with fracture line in the transition zone of parasymphysis-body area and exclusion criterion was Human cadaveric mandible with atrophy and pathology.

Procedure

Evaluation Criteria:
The models were assessed for
1) The structural deformation of twin fork shaped plate and 3-dimensional titanium plate following application of highest occlusal force.
2) The von mises stress generated in twin fork shaped plate and 3-dimensional titanium plate following application of highest occlusal force.

Procedure
The study was conducted in the Department of Oral and Maxillofacial surgery, The Oxford Dental college and hospital in collaboration with Tejvi Techno Solutions, Bangalore on three-dimensional finite element computer model generated on the basis of measurements from a human cadaveric model of the mandible in STL format extracted from the CT scan. Ethical clearance was taken from the institutional ethics committee. Computerized tomography data were obtained from a Siemens Somatome Sensation Multi-slice for a full human skull at every 1.5 mm in the horizontal plane. The data were from a 22 year old male who had full dentition and normal occlusion.5 The CT data were then imported into Mimics 7.3 (Materialise, AnnArbor, MI) in image format in order to convert the scans into a 3D IGES format suitable to import into any FEA/CAD program. Manual editing was then done in order to separate the dentate mandible from the skull data. Fig 3a, 3b, 3c shows sections for cortical bone and cancellous bone that were designated their own masks by use of tools available in Mimics. Manual editing was used on a number of occasions when the resolution of the CT scans did not show clear boundaries between osseous materials. Manual editing uses draw, erase, and local thresholding functions to locally add and subtract from a mask in any of the 2D orthogonal planes. Care was taken in mask designation of half of the mandible as symmetry is taken advantageous in reflecting the geometry across the sagittal plane in ANSYS.

Construction of the basic finite element model (FEM) of mandible
The three-dimensional finite element computer model was generated on the basis of measurements from a human cadaveric model of the mandible extracted from the CT scan. A xyz coordinate system was assigned to the model (x direction-antero-posterior, y direction-supero-inferior, and z direction-medio-lateral). The geometry data was imported into a generally accepted, and already commercially available, FEM program, ANSYS 18. The properties of the bone were assumed to be isotropic, homogenous, and linearly elastic.2The behavior of the bone was characterized by two elastic constants-Young modulus and Poisson ratio. (Young modulus-13700 MPa, and Poisson ratio-0.26)

Construction of finite element model of titanium plates with screws
The dimensions and specifications of the different designs of conventional titanium miniplate and screws was entered into the software (Solid Edge V19), and three-dimensional were created with exact geometry. Material properties for titanium were assigned as 110000 MPa for Young modulus and 0.34 for Poisson ratio.2The fracture site in the transition zone of the parasymphysis–body region was determined and different assemblies of miniplate were applied.

Occlusal loading
A bite force of 570 N was applied over the occlusal surface of the generated model while keeping the condylar and coronoid processes fixed.2 With an adequate and simplified geometric finite element model and the appropriate material properties, along with the highest occlusal loading and support conditions, the finite element solver module of the ANSYS software carried out the mathematical procedure, and displacement and stress values for each node as well as element was obtained.

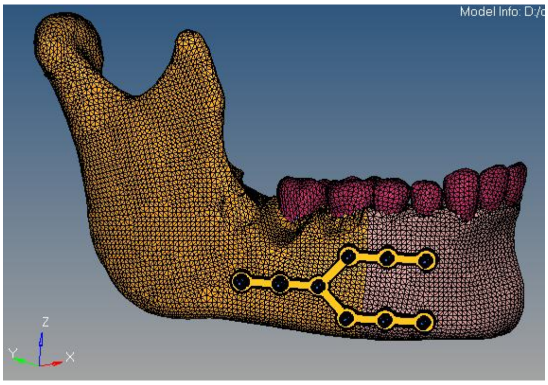

Figure 6 (a): Placement of the Plate with the screws (model 1)

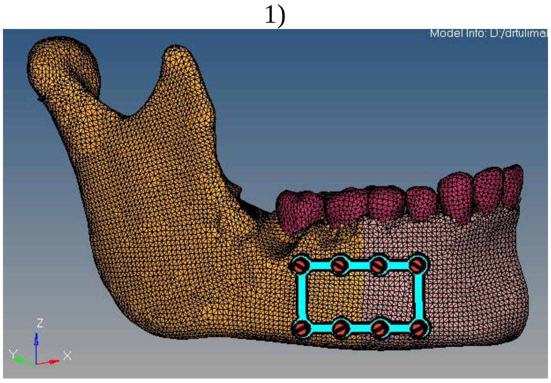

Figure 6 (b): Placement of the Plate with the screws (model 2)

Finite element analysis

By analyzing the von Mises stresses by the model for each configuration, and the total structural deformation of the miniplates in each configuration, we analyzed which configuration of miniplate and screws provided the greatest stability.

This finite element study will attempt to determine if model 1 is comparable to model 2 in terms of structural deformation, the total stress generated in the bone and in the plates. The comparison will use von Mises stress in the cortical bone surrounding the screws indicative of the likelihood of bone damage and relative displacement or the structural deformation along the fracture line that can affect delayed healing and nonunion. von Mises criteria were chosen in order to be consistent with prior studies of similar nature.6[-9]von Mises Stress values have been shown to be within 15% of Tresca.1[0]

3. Results

1) Total structural deformation

Results indicated that the total structural deformation for the twin fork miniplate after applying maximum occlusal bite force was lesser, 5.4932mm. This compared with 6.54874 mm for the 3-D miniplateconfiguration. (table 1, & Fig a, b)

Table 1: Total structural deformation in model 1 and 2

Evaluation criteria	Model 1	Model 2
Structural deformation (mm)	5.4932	6.54874

2) Equivalent von-Mises stresses

The equivalent von Mises stresses generated for the various configurations are depicted in table 2, & fig. c and d. These were calculated to predict yielding in the fixation units (plates and screws).

The results showed that the twin-fork miniplate produced lesser stress – 1) Cortical Stress: 577.55 Mpa, 2) Cancellous stress 87.361MPa, 3) Peridontium stress: 0.002448 MPa, 4) Teeth stress: 43.79 MPa— on occlusal loading, and had the least chance of yielding when compared with the other miniplate configuration. The VM stress value for the 3-D miniplate configuaration was 1) Cortical Stress: 694.918Mpa, 2) Cancellous Stress 242.986MPa, 3) Peridontium stress: 0.004121MPa, 4) Teeth Stress: 84.3488MPa. This showed that the twin-fork miniplate, even on application of maximum forces, can provide the best stability.

The plate and implant stress for the twin fork miniplate was 1732 MPa and 1730 MPa and that for the 3D miniplate was 18.4711MPa and 141.933MPa respectively. This showed that the twin-fork miniplate, on application of maximum biting forces could withstand most of the load applied instead of transmitting it to the bone.

Table 2: Equivalent von-Mises stresses in model 1 and 2

Evaluation criteria	Model 1	Model 2
Overall Stress (Mpa)	1732	694.918
Cortical Stress (MPa)	577.55	694.918
Cancellous Stress (Mpa)	87.361	242.986
Peridontium Stress (Mpa)	0.002448	0.004121
Teeth Stress (MPa)	43.79	84.3488
Plate stress (MPa)	1732	18.4711
Implant Stress (Mpa)	1730	141.933

4. Discussion

The zone of transition at the mental foramen region is also constantly subjected to different types of occlusal and muscular forces along with tension forces on its superior border and compression forces on its inferior border. Moreover, this zone is complicated by the presence of long roots and the change in the pattern and direction of the bony trabeculae. The presence of the mental nerve in this region makes it more difficult for the surgeons to fix the fracture segments without dissecting and damaging the nerve.1This twin fork miniplate is designed to overcome all these issues.

The miniplateosteosynthesis is a standard method for the surgical treatment of mandible fractures.[11-13]Apart from easy handling, in the majority of cases it also ensures adequate fracture stability and improves bone healing; indeed, movement at a fracture line is a known predisposing factor for both infection and nonunion the rate of which has been reported to be 3.7%.[14, 15]If the internal fixation has not been correctly done or is not sufficiently rigid, the rate of postsurgical nonunion may increase. The ideal type and configuration of plate (s) to provide fixation of the fracture are not known. The first factor in planning the management of fracture is the rigidity of the repaired fracture section and second is the stress levels generated in the miniplates under bite forces. In the present study, the biomechanical behaviour of the two different configurations i. e the twin fork shaped miniplate and 3D miniplateosteosynthesis as applied to the 3D FEM of mandible were analyzed for fixation method to stabilize a fracture to compare which configuration results in less mechanical stress on the mandible.[16]

Evaluation of the biomechanical behavior of the twin fork miniplate using FEA revealed that this miniplate is superior in terms of stability. The structural deformation for this design of miniplate was lower (5.4932 mm) when compared to the other plate configuration (6.54874mm) and produced lower equivalent von Mises stresses **(**cortical, cancellous, teeth and periodontium) on application of maximum occlusal forces. Therefore, it reduces the yielding of the fixation units under stresses, and restricts any micromovements in the fracture segments as well as in the miniplate/screws and associated bone. This more rigid fixation should lead to faster healing.[2]

Several studies have shown that fixation of mandibular fractures with the miniplate and the dynamic compression plate systems give good clinical results[17, 18]and these results are influenced by both the mechanics at the fracture site and the mechanical properties of the implant.[19]The loads across the fracture are carried partially by the fragments and partially by the implant.[19]Fracture characteristics, such as direction, shape and serration may play an important role by neutralizing the loads across the fracture.[20] In smooth or comminuted fractures, inter-fragmentary stability is absent. For these fractures, the implant needs to carry a larger part of the loads across the fracture than in case of serrated fractures. In our study, the plate and implant stress for the twin fork miniplate was 1732 MPa and 1730 MPa and that for the 3D miniplate was 18.4711MPa and 141.933MPa respectively which means that the twin-fork miniplate, on application of maximum biting forces could withstand most of the load applied instead of transmitting it to the bone only.

In our study, a bite force of 575N was chosen.2The influence of fracture position and the bite point on the loads across the fracture was studied with a uniform magnitude for the bite force. However, in vivo, the bite is not of uniform maximum magnitude but increases from the incisor region to the molar region.[21]

Our simulations, like most finite element simulations, were based on an idealized model to which idealized properties (Young's modulus and Poisson's ratios) were assigned.[1, 2, 4]Shortcomings in the model included the lack of information on teeth, the insufficiency of detailed knowledge on the material properties of the cancellous bone, the unpredictability of how to realistically distribute the muscle loading, and the difficulty to know how to model the boundary conditions of the condyles. However, as we only aimed at investigating stress distribution and structural deformation rather than predicting the biological reaction, these models were completely qualified for the work. In the future, great importance should be specified to overcoming the shortcomings of the model.

There are several studies on biomechanics of the mandible that used FEM to investigate the stress strain distribution and rigidity comparison for both fixation of fractured.1[5] Fernandez et al[6] used FEM in a fractured human mandible to simulate and to study the biomechanical loads and stresses field distribution of treated with plating technique. The fracture was located in the symphysis region and one or two titanium miniplates were evaluated. Cox et al[8] used two separate FEM to assess whether rigid fixation by resorbable polymer plates and screws could provide the required stiffness and strength for a typical mandibular angle fracture. Tams et al[22] used FEM to establish the suitability of small biodegradable plate systems for mandibular angle fractures. Tams et al[23] calculated fracture mobility and plate strain in a 3D computer model of the mandible for bite forces applied on 13 bite points on the dental arch. They aimed to dictate whether a small biodegradable plate system was acceptable for internal fixation of mandibular fractures. The authors reviewed different fracture sites and several fixation position alternatives. Tams et al[24] compared bending and torsion movements across mandibular fractures for different positions of the bite point and different sites of the fracture. Three identical resin mandibles were surveyed in the study. Vollmer et al[25] found a high correlation between this method and in vitro measurements on mandibular specimens. Clinical extrapolations from mathematical models may not give actual results, but they can provide a detailed description of the stresses within natural variability.[9]

In the past, computer simulated FEA models addressed the adequacy of the mathematical models to relate mechanical factors such as load transfer to the biomechanical behavior of specimens.[15]Given a high association between the FEA and the experiment, various data within the specimen can be visualized using the FE calculation. Various authors have reported on the accuracy of FEA in describing the biomechanical behavior of bony specimens.[26-28]

The in vitro study by Datarkar et al.[2] confirms the study of Kroon et al[29] and Choi et al[30] who found that only one miniplate is not able to provide the stability to the fractured segments in this highly dynamic region and one more plate is required that acts as the tension band. The twin-fork−shaped miniplate has an upper horizontal arm that acts as a tension band and lower horizontal arm as the compression arm. Both the arms are connected to a single horizontal arm that coincide with the lines of osteosynthesis distal to mental foramen region.[1]

The present study is an attempt to determine the mechanical stress and structural deformation on the mandible after the application of highest occlusal load by means of numerical calculations, using the FEM in a 3-D elastic model which simulates the mechanical behaviour of the mandible.[31, 32]Some FEM models treated mandible as an arch with rectangular cross section.[33, 34]However, in this study we considered an accurate anatomic section of a human mandible and we distinguished between the cortical and cancellous bones. As in most reported studies, we assumed that the materials are homogenous, isotropic and linear elastic behaviour characterized by their two material constants (Young's modulus and Poisson's ratio).[35]

Additional advantages of the study include preservation of the mental nerve during the plating procedure and, as a result of the broad end of the Y-shaped miniplate, atraumatic positioning of the miniplate and hence fixation of fractured segments. Although improper handling of the soft tissues may cause neurosensory disturbances, only gentle reflection of the periosteum is required in order to insert the twin-fork-shaped miniplate in the inframental foramen region. Another mechanical advantage of this specific design is the equal distribution of the vector forces and stresses along the three arms. As a result, forces along the inner zone of the broad end of the Y shape are neutralized, with the neutral zone overlying the anatomical location of the mental nerve.[1]

The two limitations of this study are: 1) There are inherent limitations in the FEM because of its geometrical simplification/idealization, material characteristic properties, and boundary conditions.2) Further anatomical variations of the mandible and fracture cannot be considered in the analysis.[2]

The results of this FEA study are very encouraging, leading to the conclusion that the twin fork shaped miniplate is better in terms of stability. An interesting characteristic of this miniplate is its novel design[1], and fixation of the fracture segments using a minimum of four screws (two on each side of the fracture segment) upto a maximum of nine screws, in a single twin-fork-shaped miniplate.2 The use of twin-fork miniplates for fixation of transitional zone fractures of the mandible is recommended as these plates, according to FE models, produce the lowest stress values and therefore the most stable fixation.

5. Conclusion

This study concludes that the twin fork shaped miniplate is superior in terms of stability as it has shown to have less structural deformation, and produces less equivalent stresses on application of maximal occlusal forces compared to the 3D miniplate. Another advantage is the preservation of the mental nerve during the plating procedure as the broad end of the Y shape allows atraumatic positioning of the miniplate thereby the fixation of fractured segments.

This was a purely computerized, in-vitro study to evaluate the biomechanical behavior of the twin fork shaped miniplate, using FEA and compare it with the conventional 3D miniplate. Further clinical studies with large sample sizes and longer follow up periods should be performed and the studies should also include the associated maxillofacial trauma in order to evaluate the clinical use of this newly designed twin-fork miniplate in multiple trauma cases.

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Obtained

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