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Comparative Evaluation of 7 Fixation Plates in Mandibular Angle Fractures Using Finite Element Analysis

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Abstract

Background: The finite element method is a used computational technique in obtaining detailed displacement of the fractured mandible with a fixation system.
Objectives: The aim of the study was the evaluation of the biomechanical performance of different rigid fixation methods in mandibular angle fractures.
Methods: Computed Tomography (CT) scans applied to prepare a model of the mandible with a mandibular fracture angle. The fracture line was fixed with 7 different fixation plates. The CT scans were transferred and converted to the finite element model. The commercial ANSYS software was applied to analyze the Von Mises stresses and the amount of displacement on bones, plates, and screws. 150-newton vertical force was applied to central incisors in order to simulate the most critical loading.
Results: The maximum Von Mises stress values were found in the Champy technique with 474 Mpa in bones and 579 Mpa in screws, whereas the lowest Von Mises stress values observed in the square plate which was 180 Mpa. The minimum displacement observed in the Reconstructive plate & mini-plate which was 0.25 millimeters.
Conclusion: The application of Reconstructive Plate & Mini-Plate, Dual straight mini-plates, Square Mini-Plate led to lower stress and displacement than other techniques in the bone, Plate, and screw. Reconstructive Plate & Mini-Plate, Dual straight mini-plates, Square mini-plate offers more resistance and stability at the fracture site than other techniques used in the current study. This study was done based on the analysis of computer data. Clinical evidence showed that other procedures were used for many years with success. There are many other factors in the clinical application that have a critical role in stability.

Keywords: Jaw Fixation Techniques; Mandibular Fractures; Finite Element Analysis; Fracture Fixation; Internal Fixators.

Introduction

The angle of the mandible is a common site for fractions, and fracture of this angle is one of the most complications in the facial region.[1] Significant advance observed in the treatment of mandibular fractures due to advances in biomaterial, improved biomechanics principles, and scientifically based research on treatment outcomes.[2,3] Microplate fixation widely use in mandibular fractures and has become a standard treatment technique.[4] The fixation of the mandibular angle is more critical than the fixation of fractures located in other regions of the mandible.[5] Although there is a widely accepted consensus about the need for surgical procedure and the fixation of fracture in the angle of the mandible, different treatment modalities described. Numerous studies on the treatment of mandibular angle fractures reveal the fact that there is not a single, ideal modality. Biomechanical researches have a critical effect on improving the design and producing successful materials for achieving the best treatment plan.[6,7] Because of the high stress-bearing of the mandible, the Fixation of fractures in the mandibular angle is biomechanically complex.[8] Although numerous mini plates with different geometric designs are available, the number, the location of the screws, and the geometric properties of these materials have not been identified. No data are available about the treatment of fracture in the mandibular angle with various types and configurations of mini plates. Moreover, the stability provided by miniplate fixation has become a point of disagreement among surgeons.[9]

Finite element Method (FEM) is a computational technique developed by engineers that used in obtaining detailed displacement, strain, and stress distributions of the fractured mandible with a fixation system. Numerous studies have shown that the results of FEM are accurate, valid, non-invasive, and this method used to predict different parameters of the complex biomechanical characteristics of the mandible.[10-15]

Objectives

Therefore, this study aimed to analyze a 3-dimensional (3D) finite element model (FEM) to simulate seven different types of model fixation that use to determine the most suitable shape and fixation technique for mandible angle fracture. The results used to compare the mechanical behavior of each plate with other plates in terms of the stabilization of fractured segments.

Materials and Methods

A three-dimensional model of mandible was constructed from 720 serial axial sections with Cone-Beam Computed Tomography (CBCT), and each slice obtained every 0.1-0.3 mm of a 35 years old male's mandible with full dentition. The recorded images were restored in digital imaging and communications in medicine (DICOM) format and then exported to MIMICS (V19.0, Materialise b.v, Leuven, Belgium). A 3-dimensional model of mandible was created and image noises were eliminated in software and then exported to 3-Matic (Materialise b.v, Leuven, Belgium) to edit geometrical surfaces and making solid models. After comprehensive geometrical editing, the final 3D model imported to CATIA software (V5R27, Dassault Systems). In CATIA, the cortical bone was created with a thickness between 1-1.2 mm and assumed to be homogenous, linearly elastic, and isotropic in the whole mandible and the rest bone, cancellous, assumed to be homogenous too. The mandibular angle fracture line was simulated as a line from the center of the most typical location of the 3rd molar to the most inferior posterior point of the mandibular angle. Fixation plates and screws designed by reverse engineering and finally assembled to 3D model of the mandible on the fracture site. All plates and screws were modeled as the Ti-6Al-7Nb titanium alloy. The used mechanical properties in the analysis shown in Table-1. 3D assembled models of the mandible and fixation plates and screws were imported in FEA software, ANSYS WORKBENCH (Version 19.3, ANSYS Inc., Canonsburg, PA). ANSYS was used to auto-mesh the model with different types and sizes of elements as listed in Table-2. The meshed model is also shown in Figure-1. Both condyles were simulated as spherical joint then masseter and temporalis mussels were simulated as zero displacement constriction in an approximately functional direction. 150-newton vertical force was applied to central incisors in order to simulate the most critical loading. Constrictions and loading are depicted in Figures-2 and -3.

Table-1. Mechanical properties of the materials used in Finite Element Analysis.

Materials	Elastic Modulus (E), Gpa	Poisson ratio (ν)
Cortical bone	14.8	0.3
Cancellous bone	1.85	0.3
Ti-6Al-7Nb titanium alloy	110	0.34

Table-2. Types and number of elements and nodes used for different parts.

Parts	Number of nodes	Number of elements	Element type
teeth	28450	17156	Solid 187
Cortical bone	47695	24248	Solid 187
Cancellous bone	23357	13449	Solid 187
Contact elements	-	43638	Conta174, conta170, MPC184, surf154
Total	99508	98495	-

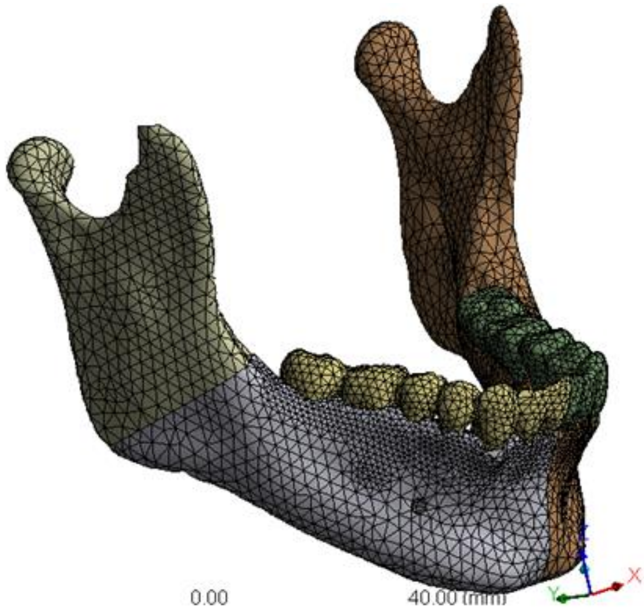

Figure-1. Meshed model of the mandible.

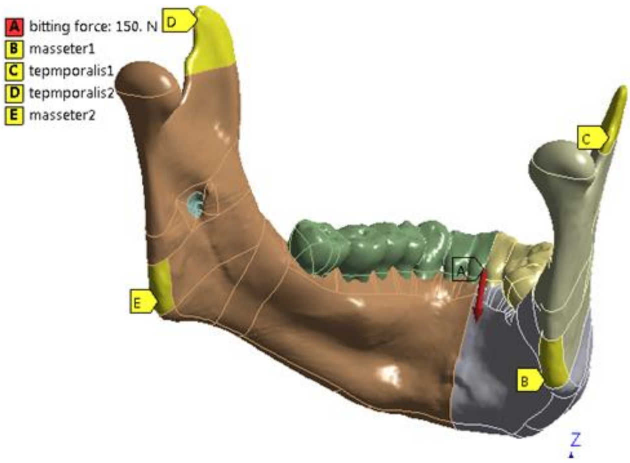

Figure-2. Biting force and muscles' constrictions.

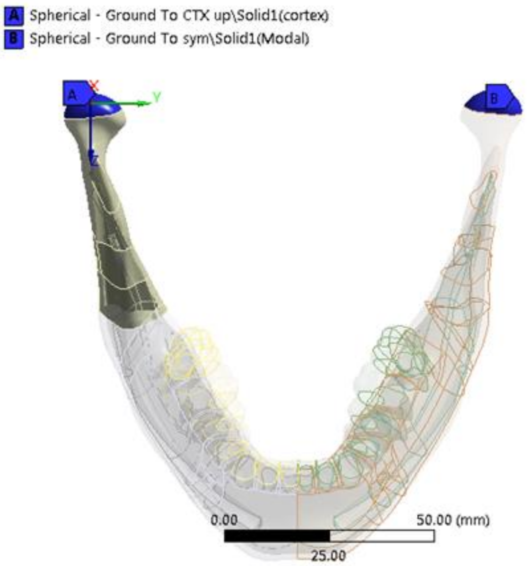

Figure-3. Spherical joints applied to condyles.

Seven different fixation plates were modeled:

1) a 6-hole reconstruction plate near the inferior border of mandibular angle and a 4-hole straight mini-plate near the superior border of mandibular angle; 2) a single reconstruction plate near the inferior border of mandibular angle with locking screws; 3) Dual 4-hole straight mini-plates in compression and tension zone; 4) a 4-hole straight mini-plate on the superior border of mandibular angle (Champy technique); 5) a single lag screw inserted near superior border of mandibular angle; 6) a 5-hole Y-plate near-neutral zone of mandibular angle; 7) a square 4-hole mini-plate inserted symmetrically around the neutral zone of the mandibular angle. All mini-plates have 1.25mm thickness, and the reconstruction plate has 1.5mm thickness. In total, seven different mini-plate models and all models with maximum Von Mises stress show in Figure 4-10.

Results

The evaluation of the finite element analysis results was achieved according to displacement and stresses in the plate. Bone, screw. After analysis of the assembled model of mandible and plates and screws under vertical loading and constrictions, the total displacements of the whole fractured segments and Von Mises stress values are shown in Table-3 and Figures-4, -5.

On comparing the seven-fixation method, the highest Von Mises stress values in plates were observed in the Single Reconstructive plate that was 1767 Mpa, whereas the lowest stress values have been found in the Square mini-plate that was 180 Mpa. The maximum Von Mises stress in bone was also observed in the Single Reconstructive plate, and the minimum Von Mises stress was observed in the lag screw and Reconstructive plate and mini-plate which was respectively 81 and 63 Mpa.

Champy technique showed the maximum Von Mises stress in the bone that was 474 Mpa; however, the Reconstructive plate & mini-plate and Lag screw had the minimum stress values in the bone that was respectively the 63 and 81 Mpa. The maximum Von Mises stress values in screw observed in the Champy technique with 579 Mpa, whereas the minimum stress values found in the Reconstructive plate & mini-plate with 201 Mpa. The lowest displacement in bone and plate was observed in the Reconstructive plate & mini-plate that was respectively 0.25 and 0.065 millimeters. Single Y-plate had the maximum displacement in bone, plate, and screw that was respectively 0.52, 0.21, 0.2 (Table-3). Maximum Stress and displacement in different parts are shown respectively in Table-3 for each fixation method. The maximum displacement in millimeters and maximum Von Mises stress in MPa for bones, plates, and screws present in Table-3, Figures-4 and -5.

After probing the displacement on the fracture zone between two fractured segments, the maximum displacement in two following directions, normal to fractured surface and parallel to fractured surface was extracted [16] and shown in Table-4. Single Reconstructive plate had the highest displacement in the un-fractured and fractured surface that was 152 µm. The Champy technique showed the maximum displacement in the fractured surface was 185 µm. The minimum displacement in the unfractured and fractured surface was seen in the Reconstructive plate & mini-plate and was 40 µm (Table-4).

Table-3. Maximum displacement (mm) and Von Mises stress (Mpa) in different parts

Fixation Method	Bone		Plates		Screws	
	Mpa	mm	Mpa	mm	Mpa	mm
Reconstructive plate & mini-plate	63	0.25	233	0.065	201	0.064
Single Reconstructive plate	122.7	0.44	1767	0.14	304	0.13
Dual straight mini-plates	111	0.28	283	0.09	205	0.09
Champy technique	474	0.35	311	0.154	579	0.15
Lag screw	81	0.33	NA	NA	247	0.14
Single Y-plate	92.5	0.52	379	0.21	256	0.2
Square mini-plate	129	0.34	180	0.11	320	0.106

Table-4. The maximum displacement in two perpendicular directions in the fractured surface.

Fixation method	Normal to fractured surface (µm)	parallel to fractured surface (µm)
Reconstructive plate & mini-plate	40	-
Single Reconstructive plate	152	-
Dual straight mini-plates	49	-
Champy technique	38.8	185
Lag screw	36.5	137.3
Single Y-plate	117	184
Square mini-plate	82.8	-

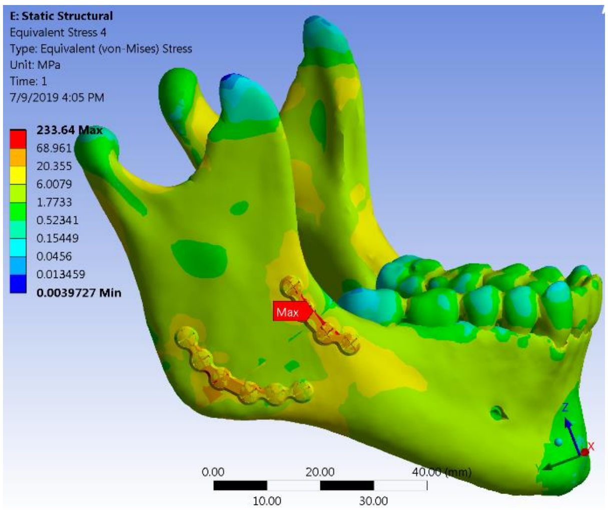

Figure-4. Maximum stress in Reconstructive plate & mini-plate

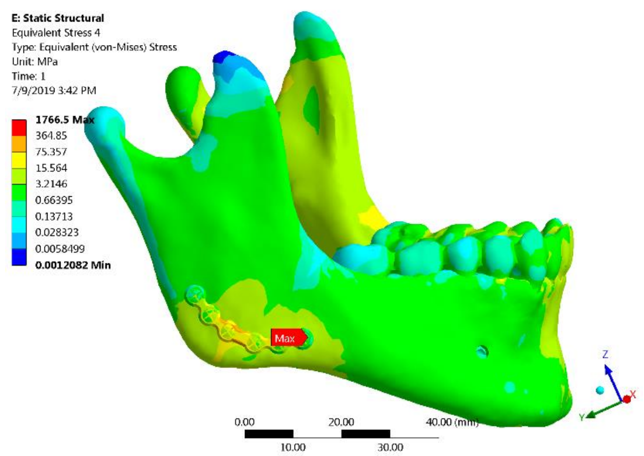

Figure-5. Maximum stress in Single Reconstructive plate

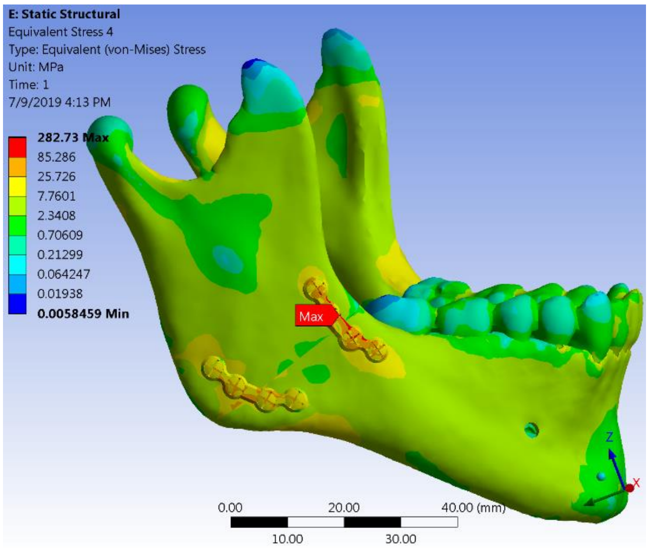

Figure-6. Maximum stress in Dual straight mini-plates

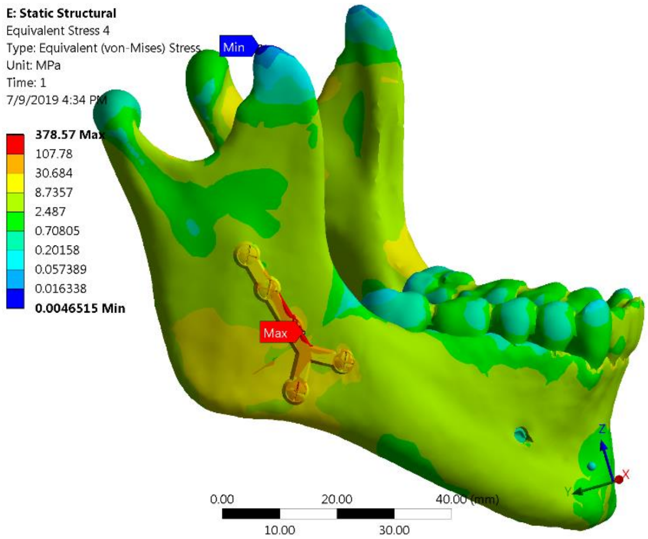

Figure-9. Maximum stress in Single Y-plate

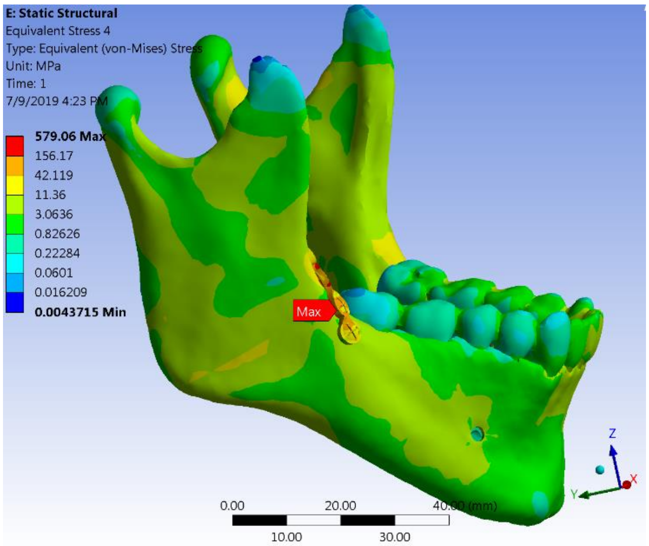

Figure-7. Maximum stress in the Champy technique

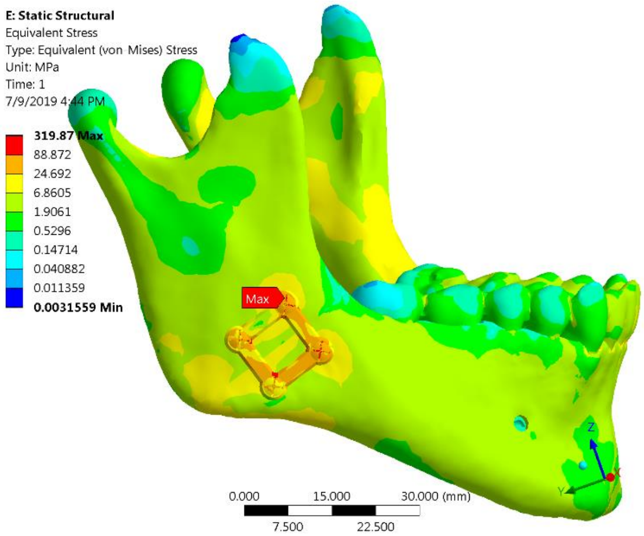

Figure-10. Maximum stress in Square mini-plate

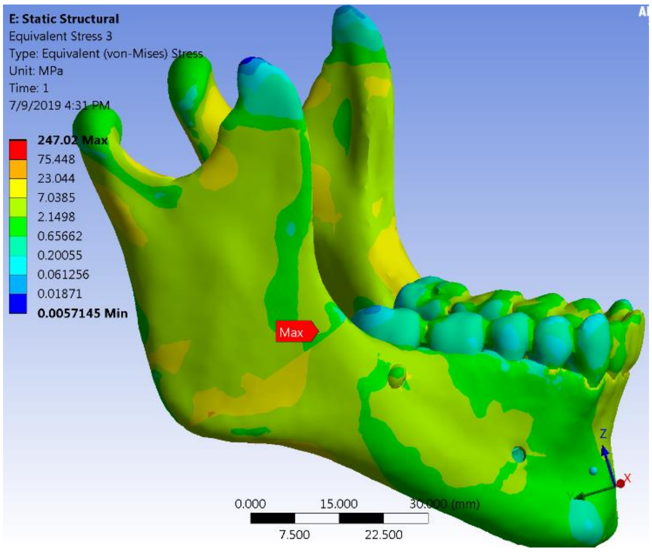

Figure-8. Maximum stress in Lag screw

Discussion

In the treatment planning of the mandibular angle, the selection of plate type is critical. The first principle is the rigidity of the fracture section, and the second is the stress levels in mini plates during bite forces.[17] Therefore, the biomechanical properties of seven different types of mini-plate that were used in the mandibular angle area were analyzed by FEM in this study. Finite element analysis is an analytical system widely used in engineering and can be applied to unravel complicated problems in oral and maxillofacial sciences. This method was selected for this research due to the complexity of the clinical design, diversity of plates needed to be matched, individual response to force applied, ethical problems, and the potential effect of other variables. Besides, FEM is the closest condition to the clinical procedure in simulating the maxilla mandibular environment. [18] This study showed that the amount of displacement was the lowest one respectively in Dual straight mini-plates and Reconstructive plate & mini-plate. That is why both of these plates are recommended from the stability of bones. Single Y-plate had the worst results. Reconstructive plate & mini-plate, Dual straight mini-plates, Square mini-plate had the lowest displacement and also had the least amount of Von Mises stress in plates. Therefore, these three mentioned plates are recommended from the view of stability and stress on a plate. The amount of Von Mises stress in bone and screw was the highest one in the Champy technique. That is why this plate is not recommended for mandibular fracture. Different plates and screws with different geometric designs have been applied in the treatment of angular mandibular fractures.[19] This study showed that Champy's mandibular plate has low rigidity and stability in angle fractures, however, this plate has been widely used by oral and maxillofacial surgeons in cases of trauma to the maxillofacial region.[20] It has been reported that Champ's technique has the lowest morbidity rates, and the fewest postoperative complications to treat mandible angle fractures.[21] Champy's method is preferred by many surgeons due to the size and adaptability of the miniplate, consequently make it easy to apply through an intraoral approach, Kroon et al [22] have stated Champy's method to be related to poor rigidity, poor resistance to torsional forces, and poor stability in the angle of mandibular fractures. This result encouraged scientists to research new methods that aim to overcome these side effects. Several studies showed that the use of the two-miniplate fixation methods to treat mandibular angle fractures provides better stability in comparison with Champy's technique.[9, 22-28] Similarly, this study showed that due to the highest amount of Von Mises stress in bone and screw in Champy's technique, which was 474 and 579 Mpa respectively, is not a good miniplate between others.

Niederdellmann et al [29] reported a radically different treatment procedure using a lag screw, which is used for fixation without the use of plates. Lag screws have proven to be technically difficult and have thus not gained popularity. It has been shown that the lag screw method provides greater fixation in selected mandibular angle fracture cases. [23] The result of this study showed that the amount of Von Mises stress in lag screw in bone and also in the screw is not much and it suggests that this type of fixation provides a good candidate for fixation.

Because the square plate is arranged in the configuration of a box on both sides of the fracture, this broadband configuration increases the resistance to twisting and bending to the long axis of the plate. This simultaneous stabilization of the tension and compression zones makes the square plate make a better alternative to the conventional zone.[8] Moreover, Atik et al[20] analyzed the mechanical property of different rigid fixation methods in mandibular angle fractures. Also, it showed that the lowest amount of stress has been found in the square plate. The current study showed that the amount of Von Mises stress in Square mini-plate was in the lowest one and also showed that the rate of displacement of bone was 0.11 millimeters that were in the minimum limit between the other seven techniques. This study showed that this system can be suggested as an alternative for an angular fracture of the mandible. Atik et al[20] reported that Y plate screw had higher stresses among other miniplate configurations. This property can be related to the design of the Y plate that prevents homogeneous load transfer along with the plate and screws. Similarly, this study showed that amount of Von Mises stress in bone plat and screw is higher than other systems, and this system is not recommended for angular fracture of the mandible.

Singh et al. [30] assessed 51 patients with fracture of mandibular angle and treated with a single miniplate. The authors reported that the single miniplate fixation method is unfavorable. The current paper showed that the Von Mises stress in a single miniplate is 1767 Mpa and it is not recommended for mandibular angle fracture.

Schierle et al. [9] reported that the two-plate fixation does not seem to have advantages over single-plate fixation. On the contrary, Ellis[31] stated that the use of a single miniplate was related to fewer complications than if two plates were used. On the other hand, this current study showed that the amount of Von Mises stress in bone plate and screw was in the lowest on in dual plate in comparison with a single plate and this FEM study showed that the amount of bone displacement in the dual plate was lower than a dual single plate that is why the dual plate is better than single plate from the view of stability.

In this computer-based study, only the stability of fixation was evaluated. Some factors such as infection rate, systematic diseases of patient, quality of bone, and so on have an important role in stability. For example, the lowest infection rate, 7.5%, was seen in the fractures treated with the AO reconstruction plate the highest rate, 32%, was found in the 2.4-mm dynamic compression mini plates. The dynamic compression plates and the non-compression plates each had an infection rate of around 25%. Interestingly, it was noted that in the group of fractures treated with the 2A-mm dynamic compression plates, the mandibles that had fixation screw holes tapped had a lower incidence of infection than those that were respectively untapped-29% and 40%. Consequently, smaller plates have an increased rate of infection, possibly because of a lack of providing absolute rigidity. In this series of articles, only the AO reconstruction plate was found to provide a predictably low incidence of complications.[32-35]

Conclusions

This study demonstrates that three-technique such as Reconstructive plate & mini-plate, Dual straight mini-plates, Square mini-plate offers more resistance and stability at the fracture site than other techniques used in the current study. FEM confirmed that the three mentioned plates could be used successfully in angular mandibular fractures. This study is an in-vitro study, therefore, it cannot be concluded that only these three techniques can be applied for clinical purposes. There are many other factors in the clinical application that have critical roles for stability. Clinical evidence showed that other techniques were used for many years with success.

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None.

Authors' Contribution

All authors pass the four criteria for authorship contribution based on the International Committee of Medical Journal Editors (ICMJE) recommendations.

Conflict of Interests

The authors declared no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

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