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Evaluation Of Stress And Strain On Surgical Screws And Plates In Mandibular Trunk Fractures At Different Positions Of Plates And Screws: Finite Element Analysis

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ABSTRACT

Introduction: To determine the most appropriate method for placement of plates and screws in terms of stress in mandibular body fractures using finite element analysis.

Materials and Methods: First a model of the mandible reconstructed with Mimics software. This study employed various methods, including plates positioned parallel to the inferior border of the mandible with screws perpendicular to the bone; plates parallel to the inferior border of the mandible fixed with screws oriented at a 45-degree to the fracture line; plates positioned perpendicular to the fracture line fixed with screws perpendicular to the bone; plates perpendicular to the fracture line and fixed with screws oriented at a 45-degree to the fracture line. Then the software measured the stress within the screws and plates in each condition under the maximum bite force.

Results: It was observed that in cases of favorable horizontal fractures, the stress exerted on the plates and bones is greater when the plates are aligned parallel to the lower border of mandible, compared to when the plates are positioned perpendicular to the fracture line. In the study of unfavorable horizontal fractures, when the plates were fixed perpendicular to the fracture line, higher magnitudes of stress were recorded compared to the stress observed in the plates positioned parallel to the inferior border of the mandible.

Conclusion: In cases of mandibular body fractures with favorable horizontal orientations, the use of fixation techniques involving plates perpendicular to the fracture line is preferred due to the reduced stress exerted on the plates. In the unfavorable horizontal fractures, the stress levels do not exhibit significant variation between different fixations. Finally, it is not advisable to utilize screws positioned at a 45-degree angle to the fracture line, as it can lead to an increase in the displacement of the plates.

Keywords: Finite element analysis; Mandibular fracture; Stress and strain; Surgical plates and screws.

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Introduction

The face is considered one of the most vulnerable areas of the body and the incidence of trauma to the facial region is much more than that of the other parts of the human body [1,2]. Maxillofacial fractures are among the most common problems in traumatized patients, requiring special attention for diagnosis and treatment [3]. According to recent studies in 2020, the majority of facial fractures in Iran are related to the lower face region, specifically the anatomical areas of the mandible, maxilla, and zygomatic bone [4]. Fractures of the facial bones, especially the mandible, which is the only movable bone in the face, are the most common injuries referred to hospital emergency departments [4]. Published reports indicate that the most common sites of fracture in facial and jaw trauma are the mandible (27.3%), followed by the zygomatic bone (20.9%), and nasal bone (18.8%) [5]. Road accidents have been reported as the main cause of mandible fractures [6].

Bone fracture refers to a condition where the continuity of the bone is completely disrupted or severely fragmented. Bone fractures usually occur as a result of trauma, but certain pathological conditions can also lead to bone fractures. Fractures of the lower jaw are desirable when the muscles tend to bring the bone fragments close together, but they are undesirable when the bone fragments are displaced by muscular forces. Titanium is the most common material used for plates and screws and is the gold standard for rigid-fixation plates and screws. It is biocompatible, strong, and stiff [7]. Rigid internal fixation with plates and screws is now a widespread method for handling bone fractures [8]. Two commonly used methods for fixation are placing plates parallel to the lower border of the mandible or perpendicular to the fracture line.

Plate stability is achieved by locking them with screws. In 1976, finite element analysis (FEA) was first used for dental implants, and its use quickly expanded in this field. The main challenge in simulating the mechanical behavior of implants lies in modeling bone tissue and its response to mechanical forces. Accurate modeling and analysis decisions are crucial for successful modeling. Some of these decisions, which have a significant impact on finite element analysis results, include detailed and realistic bone and implant modeling, material properties definition, boundary conditions, and definition of the bone-implant interface [9,10]. The finite element analysis method is employed to analyze stress and strain in any type of geometric structure. The type, order, and number of elements significantly influence the accuracy of the results. Finite element analysis is an approach that effectively reproduces the complexity and mechanical parameters of body tissues by creating a reliable physical test model [11]. Various studies have been conducted on the appropriate placement method of plates for the treatment of mandibular angle and sub-condylar fractures using Finite Element Analysis [12,13]. There has been relatively little study on an optimal method of internal fixation. The aim of this study is to compare the stress and strain in the screws and surgical plates in fractures of the mandibular body in different fixation methods.

Materials and Methods

Preparing the model

The first step is to reconstruct the mandibular model using the CBCT images of the mandibular region of patients referred to the maxillofacial surgery department of the School of Dentistry, Tehran University of Medical Sciences with the help of Mimics Research 21.0. The inclusion criteria for the subject in this study was patient with intact mandible, normal occlusion and dentition in the anterior and posterior regions. After creating the three-dimensional model of the mandibular region, favorable and unfavorable horizontal fractures were designed on the model. To create favorable and unfavorable horizontal fractures, respectively, a fracture line with a 20-degree clockwise angle and a 20-degree counterclockwise angle was generated. The distance between the two segments after creating the fracture was set to 0.1 millimeters. In the next step, the design of 4-hole plates and screws for fracture fixation was performed. The design of the screws and plates used in this project is based on the product catalog of Synthes company (Switzerland). Both plates used in the study have four 2mm diameter holes, and the thickness of the plates is 1mm. Each plate was fixed in direct contact with the bone on both sides of the fracture line using four mono-cortical screws, each with a length of 7mm and a diameter of 2mm. All components including the mandible, plates, and screws are assembled using 3-matic Research 13.0 software. Subsequently, in both types of favorable and unfavorable horizontal fractures, both plates were reconstructed once parallel to the inferior border of the mandible and once perpendicular to the fracture line in the 3-matic Research 13.0 modeling software. One of the plates was placed in the compression zone and one in the neutral zone (Figure 1-4). In the treatment of fractures, screws are usually placed straight inside the holes, but sometimes

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the surgeon empirically places the screws at an angle in the end layer of the hole and then tightens them, which brings the fractured bone fragments closer. The purpose of introducing this factor is to investigate the positive or negative effects of angulated screw placement on stability and rigidity. Each of the plate fixation methods was reconstructed in the modeling software with two different screw placement methods, including perpendicular screw placement to the bone and screw placement at a 45-degree angle relative to the fracture. In total, 8 models have been examined.

Finite Element modeling

Then, the geometric model was imported into Abaqus software analysis. In this software, mechanical properties, boundary conditions and loading were applied to the model. The modeling steps are described in the same order as in Abaqus modules. In this stage, the three-dimensional model, including the lower jaw with various fractures (two separate bone pieces) and the placement of screws and plates (8 screws and 2 plates), were separately imported into the software as 12 parts through the Part module, and through the Assembly module, all the imported parts were positioned in their respective locations.

Property module

In this module, the mechanical properties of the model are defined. To determine the properties of titanium, reference was made to the book "Material Selection" by Mr. Ashby, where the density of titanium is assumed to be 4.43 grams per cubic centimeter, Young's modulus is 110 gigapascals, and the Poisson's ratio is 0.3. Additionally, using the stress-strain curve of the Ti6Al4V alloy, obtained through experimental tests for defining the elastic and plastic properties of titanium, plastic properties were also defined to increase the accuracy of the model. Furthermore, for defining the mechanical properties of the mandible, a density of 1.8 grams per cubic centimeter and Young's modulus of 10.2 gigapascals were considered, along with a Poisson's ratio of 0.3.

Step module

In this study, since the system lacks motion under acceleration and is quasi-static with very small displacements, a static step was considered for ease of simulation and simplification of the finite element model. Furthermore, a time interval of 60 days was chosen to examine the level of stress and strain generated in the screws and plates.

Interaction module

In this module, contact between surfaces is defined. Two types of contacts are considered in this model:

a- Contact between screw and plate.

b- Contact between screw/plate and bone.

The contact between titanium-titanium was defined as a Tie contact, and the contact between bone-titanium was defined as standard contact in Master-Slave configuration, with the Master part being the metal and the Slave part being the bone. Additionally, the contact behavior was defined in two forms: normal behavior using hard contact and tangential behavior using a friction coefficient of 0.8.

Load module

In this module, the boundary conditions and loading conditions are determined. The loading was applied to the anterior region of the mandible 50 times per day with a force of 430.4 Newtons (14) in the form of a sinusoidal wave with increasing magnitude over 60 days. This was done to simulate the scenario where the patient gradually applies higher forces after surgery.

Mesh Module

In this module, the elements of the model are meshed. In this study, all meshes were triangular meshes, and the maximum edge distance in the meshing was 0.5 millimeters. Additionally, the total number of elements in each model was approximately 1 million elements.

Results

After completing the Finite Element modeling, by applying a force of 4.430 Newtons the stress and strain exerted on the screws and plates were obtained and examined on the 60th day (Table 1).

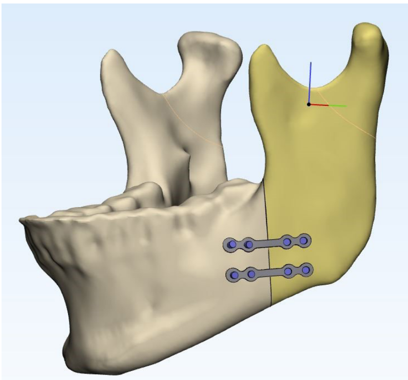

Figure 1. A favorable fracture fixed with perpendicular plates.

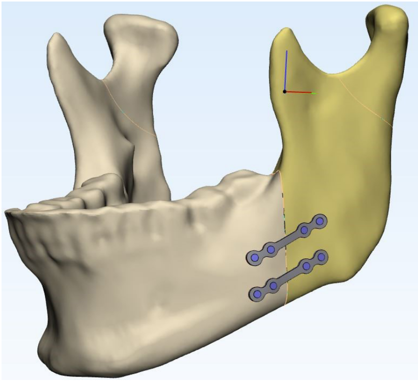

Figure 2. A favorable fracture fixed with parallel plates.

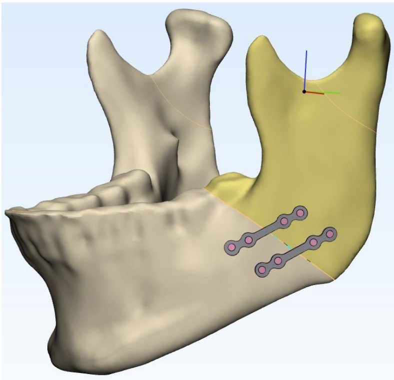

Figure 3. An unfavorable fracture fixed with parallel plates.

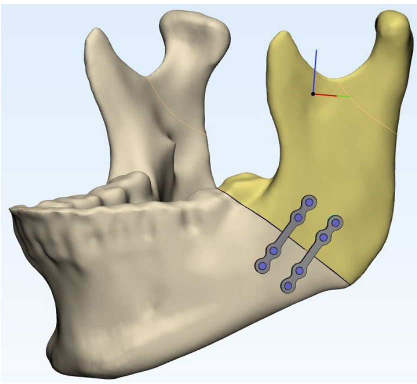

Figure 4. An unfavorable fracture fixed with perpendicular plates.

Discussion

Various studies have been conducted comparing treatment methods for lower jaw fractures using different plate shapes and quantities in terms of stress and plate deformation. Currently, there is a consensus that the use of two plates for fracture fixation is more suitable than using a single plate [13]. However, there is a lack of studies regarding the different configurations of two plates and screws in favorable and unfavorable horizontal fractures of the mandibular body. Finite Element Analysis (FEA) is a valid, accurate, and non-invasive method for biomechanical measurements, including stress and strain. In a study, the amount of displacement in the plates used for mandibular fracture fixation was measured using in vitro laboratory testing and compared with the results obtained from FEA. The comparison of the results from these two studies revealed a high correlation coefficient (0.992) and very close agreement between the two studies [15]. By examining the levels of stress and strain on the screws and plates, it is observed that in all cases, the stress distribution is higher in the upper plate compared to the lower plate. Furthermore, stress concentration occurs in regions close to the fracture line. Additionally, by analyzing strain contours on the plates, it can be observed that the lower plate is subjected to significant tensile forces, resulting in a deformation of approximately 0.5 millimeters. This deformation is primarily due to the bending forces exerted during mastication.

In favorable horizontal fractures of the mandibular body, fixation using plates perpendicular to the fracture line generates lower stress on the plates, leading to less screw loosening and bone loss in the region, so it can be concluded that it is a better treatment compared to fixation with plates parallel to the inferior border of the mandible. In unfavorable horizontal fractures, stress levels are consistently higher than in favorable fractures, and there is no significant difference in stress distribution among different fixation methods.

Moreover, the stress generated on the plates differs considering the orientation of the screws relative to the bone surface. The deformation of the plates and screws are lower when the screws are positioned perpendicular to the bone surface within the plates compared to an inclined orientation. Some limitations of this study include the lack of modeling of soft tissue, which have an impact on the boundary conditions near the fracture line, and the muscles that exert tension on the bone segments, potentially leading to different results compared to an in vivo study.

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Table 1. The stress exerted on the plates on the 60th day.

Faracture	Fixation method	Upper plate stress (N)	Lower plate stree (N)
Favorable	Parallel plates and normal screws	362	189
	Parallel plates and ublique screws	313	272
	Perpendicular plates and normal screws	219	197
	Perpendicular plates and ublique screws	215	194
Unfavorable	Parallel plates and normal screws	324	155
	Parallel plates and ublique screws	335	236
	Perpendicular plates and normal screws	394	151
	Perpendicular plates and ublique screws	411	176

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Conflict of Interest

There is no conflict of interest to declare.

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