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Evaluation of Stress Distribution in Titanium and Magnesium Mini Plates for Mandibular Fracture Fixation Across Varying Thicknesses and Fracture Orientations in Dental Applications

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Abstract

This study evaluates the stress distribution in titanium and magnesium mini plates used for mandibular fracture fixation, focusing on the impact of plate thickness and fracture orientation. Using finite element analysis, we assessed the stress levels at three thicknesses (1.25 mm, 1.5 mm, and 2.0 mm) of mini plates across favorable and unfavorable fractures. For titanium plates, the maximum stress observed was 49.81 MPa at 1.25 mm thickness in vertical fractures, decreasing to 34.87 MPa at 1.5 mm but increasing to 38.36 MPa at 2.0 mm. In contrast, magnesium plates showed maximum stress of 37.94 MPa at 1.25 mm, with a notable decrease to 30.15 MPa at 1.5 mm, ultimately reducing to 26.53 MPa at 2.0 mm. Results indicate that magnesium plates maintain lower stress levels across thicknesses, which is particularly advantageous in favorable fractures, with stress levels of 30.65 MPa and 28.07 MPa at 1.25 mm and 1.5 mm, respectively. In unfavorable fractures, magnesium plates also exhibited lower stress than titanium plates, reinforcing their suitability for patients with lower bone density. These findings highlight the importance of selecting appropriate materials and thicknesses based on specific fracture characteristics. Magnesium plates may provide a more stable mechanical environment, whereas titanium plates are preferred in scenarios that require higher mechanical strength. This study offers critical insights for optimizing surgical outcomes in mandibular fracture treatments, suggesting further research into the long-term clinical implications of both materials.

Keywords: Mandibular fractures; Titanium mini plates; Magnesium mini plates; Finite element analysis; Stress distribution.
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1. Introduction

The mandible is a part of the maxillofacial bone and is highly vulnerable to fractures. Owing to its prominent position in the facial skeleton, the mandible is the second most common bone involved in maxillofacial fractures.[1,2] In the mandible, the angle is the most common site of injury, with an incidence of 12-30%. The goal of any fracture management is to restore anatomy and function with the least morbidity. The management of these fractures has made significant progress over the past few years because of a better understanding of biomechanical principles and advances in biomaterials.[2] Despite this, mandibular angles have a high rate of post-surgical complications due to their posterior position and biomechanics, and several complications (up to 32%), such as re-fractures, infections, malunion, malocclusions, or facial nerve damage, have been reported.[3]

Treatment choices for craniofacial fractures include closed or open techniques based on the type of fracture. Traditional osteosynthesis, maxillomandibular fixation, and plate or screw osteosynthesis are routinely used. Miniplates have been used during the last decade to facilitate stability between bony fragments in the maxillofacial region and are currently the preferred surgical method for the fixation of fractures and osteotomies. One mini-plate, two-mini plates to lag screw or a single rigid plate are common variants.[4] Titanium alloy is the primary choice for rigid fixation in craniomandibular fractures

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because of its high strength and stiffness, osseointegration capacity, biologically inert nature, and bone healing. However, the disadvantage of titanium is its modulus of elasticity, which is not compatible with bone and may lead to complications such as failure of fixation. In addition, permanent fixation of metal in bones necessitates a second surgery for its removal, which can be associated with bone growth impediments and contraindications for medical imaging, such as Magnetic Resonance Imaging (MRI). Polylactic acid plates and polymer-based screws, which can degrade after bone fusion, were tested. However, their strength, stress, load-bearing ability, and foreign-body reactions are debatable. Magnesium is a biodegradable and biocompatible metal with better tensile and torsional strength than polymer materials and stimulates new bone formation.[5]

Existing practical techniques for stabilizing fractures are primarily based on clinical experience. A systemic meta-analysis also showed that the single miniplate technique was better in comparison to the two miniplate techniques with regard to the incidence of postoperative complications.[3,6] Despite various investigations, isolated case reports, and case series, there is significant controversy regarding ideal fixation techniques and the type of metal used. Hence, we considered two different materials, titanium and magnesium, in our study. Any newer experiments with materials other than titanium need to be validated using models prior to testing on humans. Finite element analysis (FEA) is an applied engineering branch that creates computer-generated models that provide various biomechanical states and understand the displacement, strains, and stresses induced in living structures using various forces. Many experimental studies have simulated fractures at the mandibular angle in a model.[7] This study was conducted with the objective of analyzing the stress distribution in the screw and mandible when screws of two different materials-titanium and magnesium, and with different thicknesses were used to treat mandibular angle fractures.

2. Materials and methods

This study was conducted in collaboration with the Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal, the Department of Oral Medicine and Radiology, and the Department of Oral and Maxillofacial Surgery, Manipal College of Dental Sciences, Manipal. Ethical clearance was obtained from the Institutional Review Board (IRB) with approval number [IEC: 49-2022].

2.1 Materials

This study aimed to evaluate the mechanical performance of titanium and magnesium mini plates used in mandibular fracture fixation, specifically focusing on their stress distribution under varying thicknesses and fracture orientations. FEA was employed to simulate the biomechanical environment of the mandible, allowing for an accurate assessment of stress levels in response to different loading conditions. Titanium plates, known for their high strength and stiffness, were compared with magnesium plates, which offer a favorable strength-to-weight ratio and potential biocompatibility advantages.[3,6-8] Table 1 shows the properties of the materials considered in the study.

Table 1. Properties of materials considered in the present study.

Property	Titanium (Ti)	Magnesium (Mg)	Mandible Bone
Density (g/cm³)	4.51	1.74	1.2 - 2.0
Young's Modulus (GPa)	110	45	10 - 20
Ultimate Tensile Strength (MPa)	860	275	100 - 150
Yield Strength (MPa)	480	160	70 - 100
Poisson's Ratio	0.34	0.29	0.30
Biocompatibility	Excellent	Good	N/A

The materials were analyzed at three different thicknesses: 1.25 mm, 1.5 mm, and 2.0 mm, across various fracture types, including favorable, unfavorable, and vertical fractures. The stress values were recorded and analyzed to determine the mechanical efficiency of each plate type under simulated physiological conditions. This approach provides a comprehensive understanding of how material choice and plate design influence stress distribution, thereby informing the optimal surgical practices for mandibular fractures. Three types of fractures (vertical, favorable, and unfavorable) were simulated at the angle of the mandible, as shown in Fig. 1. Virtual models of mini plates and screws (Fig. 2) of two materials, titanium, and magnesium alloy, were used to simulate osteosynthesis, stress, and deformation in the mandibular models. The simulated three-plate design is shown in Fig. 2b.

2.2 Computer-Aided Design (CAD) Modeling

A three-dimensional (3D) finite element model was developed from Digital Imaging and Communications in Medicine (DICOM) images of Cone Beam Computed Tomography images of a healthy human mandible, ensuring the absence of pathological conditions. This meticulous approach allowed for accurate simulation of the mandibular structure, facilitating a comprehensive analysis of stress distribution in response to varying material types and plate configurations. The images were first segmented to isolate the bone structure, ensuring that only the mandible, free from any pathological conditions, was modeled. The segmented data were then imported into CAD software, where the geometry was further refined and

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(a) Mandible with no slicing

(b) Orientation 1 (Vertical fracture)

(c) Orientation 2 (Unfavorable fracture)

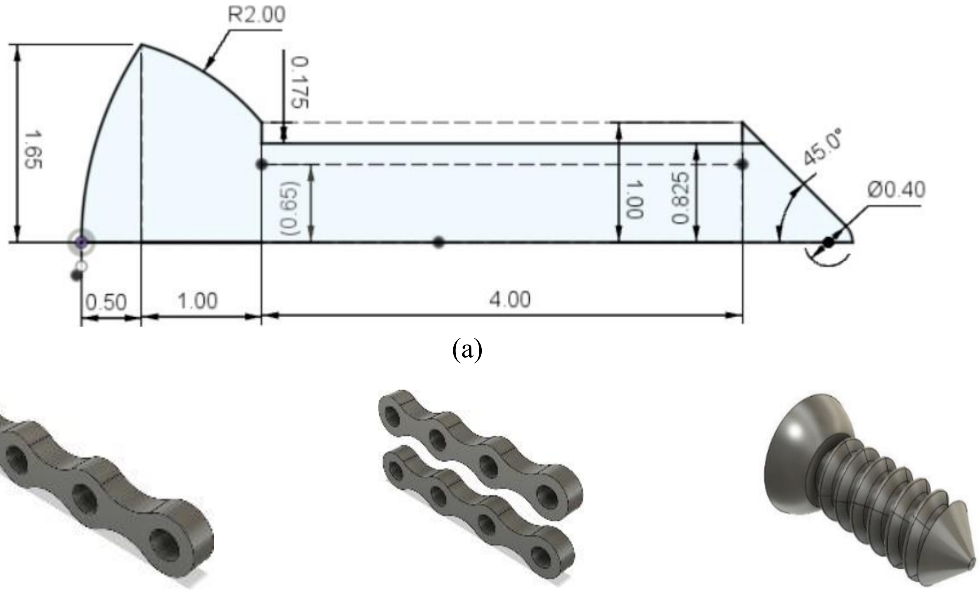
(d) Orientation 3 (Favorable fracture)

Fig. 1 3D finite element model of the human mandible under various fracture orientations. (a) Intact mandible with no slicing (b) Mandible with a vertical fracture (Orientation 1), (c) Mandible with an unfavorable fracture (Orientation 2), (d) Mandible with a favorable fracture (Orientation 3).

smoothed to create a highly accurate representation of the mandibular anatomy. This process involved converting the image-based model into a surface mesh, which was then transformed into a solid 3D model suitable for FEA. The fixation plates were designed separately based on standard clinical dimensions and configurations, ensuring precise alignment with the bone geometry. The mandible and plates meshed using tetrahedral elements, with mesh refinement in critical areas such as the fracture site and regions of high-stress concentration. This CAD modeling approach enabled the detailed evaluation of stress distribution and deformation across different plate types and fracture orientations under physiological loading conditions.

The 3D finite element model of the human mandible was developed to simulate stress distributions under different fracture orientations. As shown in Fig. 1, the model includes an intact mandible with no slicing, serving as the baseline for comparison (Fig. 1(a)); the mandible subjected to a vertical fracture, denoted as Orientation 1, which simulates a typical fracture pattern (Fig. 1(b)); a favorable fracture configuration, labeled as Orientation 2, where the fracture line follows a direction that minimizes displacement and stress concentrations (Fig. 1(c)); and an unfavorable fracture, Orientation 3, characterized by a fracture pattern that exacerbates stress and displacement under applied loads (Fig. 1(d)). These orientations were chosen to assess the performance of different material and plate configurations in stabilizing various types of mandibular fractures.

The detailed structural components used in the simulations are illustrated in Fig. 2, which presents the axisymmetric and 3D models of screws and plate configurations. Fig. 2(a) shows the axisymmetric cross-section of a screw without threads, highlighting the fundamental geometry of the screw body. Fig. 2(b) presents Plate Type 1, a single plate configuration with no gap, used to evaluate the effect of singular plate stability. In Fig. 2(c), Plate Type 2 illustrates a dual-plate configuration with two parallel plates and no interval between them, aimed at enhancing the structural integrity of the fractured mandible.



(a)

(b)

(c)

(d)

Fig. 2 Axisymmetric and 3D models of screws and plate configurations. (a) Axisymmetric cross-section of a screw without threads, showcasing the basic structure of the screw, (b) Plate Type 1: A single plate with no gap, (c) Plate Type 2: Two parallel plates with no interval between them, illustrating dual-plate configurations used in structural simulations, (d) 3D model of a threaded screw.

Fig. 2(d) displays a 3D model of a screw with threads, representing the full design used for bone fixation in the fracture simulations. These models form the basis for assessing the mechanical performance of fixation systems under different loading conditions**.**

2.3 Meshing and boundary conditions

Figure 3 shows a meshed finite element model of the mandible with a fixation plate applied. Different regions of the mandible and the plate are displayed with distinct mesh densities, representing the simulation setup used to analyze stress distribution and deformation across the bone and plate interface during mandibular fracture fixation. A mesh convergence test was performed to ensure the accuracy and reliability of the finite element analysis results. The other models of the Finite Element Model of Mandible with Mini-Plate Fixation are shown in Fig. S1.

Table 2 presents the mesh settings used for finite element analysis of mandibular fracture fixation using two types of plate designs Type 1 and Type 2 and plates made of two types of material, Titanium and Magnesium - across three different fracture orientations: Vertical, Favorable, and Unfavorable. Each orientation was modeled with three plate thicknesses (1.25 mm, 1.5 mm, and 2.0 mm). Table 2 lists the number of nodes and elements for both plate materials in each configuration.

In the FEA of mandibular fracture fixation, appropriate boundary conditions are essential to accurately simulate the physiological environment. For this study, the mandible was constrained to mimic real-life anatomical constraints. The condylar region of the mandible, which articulates with the skull, was fixed in all degrees of freedom to replicate the immobility at the temporomandibular joint. A concentrated load of 100 N was applied at the midpoint of the mandible to simulate physiological conditions during the analysis. The fracture gap was left unconstrained to allow the plates and screws to bridge the gap, simulating the process of healing. The plates were affixed to the mandible using rigid constraints at the screw insertion points, ensuring no relative movement between the bone and plate at these locations. These boundary conditions help to ensure that the simulation accurately captures the biomechanical behavior of the mandible and the fixation plates under physiological loads.

Stress (σ) can be defined as the force (F) applied per unit area (A), as shown in equation (1):

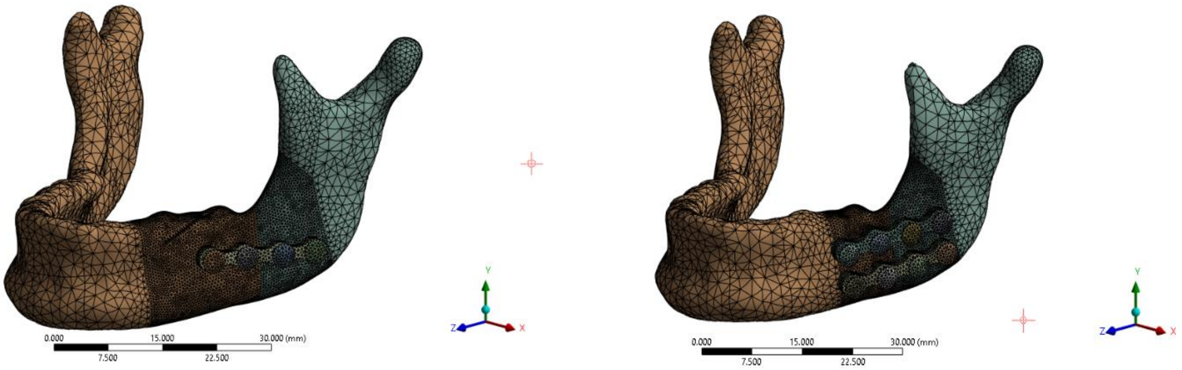
$$\sigma = \frac{A}{F} \tag{1}$$

where σ is the stress (MPa), F is the applied force (Newton), and A is the cross-sectional area (mm²).

According to the theory of failure, Von Mises stress (σv)

Table 2. Mesh settings for finite element model of mandibular fractures.

Orientation	Plate Thickness (mm)	Plate Type 1 (mm)	Plate Type 2 (mm)	Plate Type 1 (mm)	Plate Type 2 (mm)
		No. of Nodes		No. of Elements	
Orientation 1 Vertical Fracture	1.25	100678	102708	57871	59034
	1.5	102576	104564	59102	60386
	2.0	104435	107336	60338	62180
Orientation 2 Unfavorable Fracture	1.25	94949	115047	54498	66161
	1.5	95741	116920	55112	67521
	2.0	96476	119776	55616	69366
Orientation 3 Favorable Fracture	1.25	100182	120102	57336	69002
	1.5	101082	120421	58119	69398
	2.0	101656	123435	58533	71363



(a)

(b)

Fig. 3 Finite element model of the mandible with mini-plate fixation (a) Single plate (Type 1) without interval and vertical fracture. (b) Parallel plate (Type 2) without interval and vertical fracture.

is often used in FEA to determine the failure criteria as shown in equation (2),

$$\sigma v = \sqrt{\frac{1}{2}[(\sigma 1-\sigma 2)^2+(\sigma 2-\sigma 3)^2+(\sigma 3-\sigma 1)^2]} \quad (2)$$

where $\sigma 1$, $\sigma 2$, $\sigma 3$ are the principal stresses.

The reaction forces (R) at constrained nodes can be defined based on applied loads (P) as shown in equation (3),

$$R = P - K \cdot u \quad (3)$$

where K is the stiffness matrix, u is the displacement vector.

To represent element stiffness, the stiffness matrix formulation for a tetrahedral element in 3D is shown in equation (4),

$$Ke = \int B \cdot D \cdot BdV \quad (4)$$

where K_e is the stiffness matrix for the element, B is the strain-displacement matrix, D is the material property matrix, and V is the volume of the element.

3. Results and discussion

3.1 Results

The data derived from the finite element models illustrate the maximum stress values recorded for each plate type, highlighting the variations between favorable, unfavorable, and vertical fracture orientations. The findings reveal critical insights into the mechanical behavior of the plates, with specific attention to how thickness influences stress levels. These results underscore the importance of material choice and plate design in optimizing surgical outcomes for mandibular fracture treatments, providing a foundation for clinical decision making based on stress distribution patterns.

Table 3 presents the maximum stress (MPa) experienced by two types of mini-plates, titanium and magnesium, used in mandibular fracture fixation across different orientations and thicknesses. The thickness of the plates is varied at three levels: 1.25 mm, 1.5 mm, and 2.0 mm. The thickness is crucial because it influences the mechanical strength and stress distribution in the plates.

The results were categorized by plate type, with Type 1 and Type 2 in both titanium and magnesium. Each material has distinct mechanical properties that affect its stress response. In orientation 1, titanium plates show a peak maximum stress of 74.68 MPa at a thickness of 1.5 mm, while magnesium plate shows peak maximum stress at 74.06 MPa at 1.25 mm. In Orientation 2, titanium plates show a peak maximum stress of 78.18 MPa at a thickness of 1.5 mm, while magnesium plate shows peak maximum stress at 70.52 MPa at 1.25 mm. The results indicate that increasing the thickness generally leads to reduced stress levels in both materials, with variations depending on the orientation. In Orientation 3, titanium plates consistently exhibit higher maximum stress values compared to magnesium plates, particularly at 1.5 mm and 2.0 mm thicknesses. This suggests that Titanium may provide greater strength under these specific loading conditions. The results highlight the importance of material selection and design parameters in optimizing the performance of mini-plates in clinical applications for mandibular fractures. Understanding how stress varies with orientation and thickness can guide surgeons in choosing the most appropriate fixation method for enhanced patient outcomes. Table 4 outlines the maximum deformation (in mm) experienced by two types of miniplates made of titanium and magnesium across 3 orientations and 3 thicknesses. In Orientation 2, the maximum deformation for titanium plates ranged from 0.18544 mm to 0.18784 mm, while the magnesium plates exhibited slightly higher values, indicating that titanium offers better rigidity under these loading conditions. Conversely, in Orientation 3, both types of plates show increased deformation, with titanium plates measuring between 0.24279 mm and 0.24392 mm and magnesium plates ranging from 0.23929 mm to 0.24054 mm. These results highlight the impact of plate orientation and thickness on deformation behavior, emphasizing the importance of material selection and design in optimizing mini-plates for clinical applications. Understanding these variations can guide effective configurations for mandibular fracture fixation and ultimately enhance patient outcomes. Figs. S2-S13 show Maximum Stress (MPa) in the Mini Plate for Magnesium and Titanium for Type 1 and Type 2 plates.

Table 3. Maximum Stress (MPa) in the mini plate.

Orientation	Plate Thickness (mm)	Plate Type 1 (MPa)	Plate Type 2 (MPa)	Plate Type 1 (MPa)	Plate Type 2 (MPa)
		Titanium		Magnesium	
Orientation 1 Vertical Fracture	1.25	48.80	66.99	67.07	74.06
	1.5	52.55	74.68	37.57	69.88
	2.0	48.24	60.92	72.84	67.93
Orientation 2 Unfavorable Fracture	1.25	57.69	70.52	42.68	41.30
	1.5	78.18	53.85	58.57	34.42
	2.0	43.07	64.79	26.53	41.09
Orientation 3 Favorable Fracture	1.25	59.00	57.05	38.84	43.69
	1.5	75.33	75.82	75.24	57.32
	2.0	75.85	51.33	53.35	51.10

Table 4. Maximum deformation (mm) in the mini plate.

Orientation	Plate Thickness (mm)	Plate Type 1 (mm)	Plate Type 2 (mm)	Plate Type 1 (mm)	Plate Type 2 (mm)
		Titanium		Magnesium	
Orientation 1 Vertical Fracture	1.25	0.20069	0.21616	0.20660	0.21609
	1.5	0.20085	0.21683	0.20094	0.21685
	2.0	0.20121	0.21709	0.20151	0.21735
Orientation 2 Unfavorable Fracture	1.25	0.18544	0.19110	0.18589	0.19102
	1.5	0.18745	0.18978	0.18799	0.18974
	2.0	0.18784	0.19136	0.18853	0.19139
Orientation 3 favorable Fracture	1.25	0.24279	0.23929	0.24294	0.23957
	1.5	0.24305	0.23930	0.24306	0.23964
	2.0	0.24392	0.24005	0.24426	0.24054

Table 5 presents the maximum deformation (in mm) observed in the region of interest (ROI) of the mandible. In Orientation 1, corresponding to vertical fractures, the titanium plates demonstrate a maximum deformation range of 0.27776 mm to 0.27940 mm, whereas the magnesium plates exhibit slightly lower values, indicating a potential advantage of titanium in terms of structural integrity under these conditions. Figs. S14-S25 show Total Deformation (mm) in the Mini Plate for Magnesium and Titanium for Type 1 and Type 2 plates. For Orientation 2, representing unfavorable fractures, the deformations were notably smaller, with titanium plates showing values between 0.22247 mm and 0.22420 mm and magnesium plates ranging from 0.22188 mm to 0.22367 mm. This indicates that both materials perform similarly under unfavorable conditions, with only slight variations. In Orientation 3, associated with favorable fractures, the titanium plates exhibited slightly higher deformation, ranging from 0.27776 mm to 0.27932 mm, while the magnesium plates remained consistent with values between 0.27634 mm and 0.27775 mm. Figs. S38-S49 show Total Deformation (mm) in the Mandible for Magnesium and Titanium for Type 1 and Type 2 plates.

Table 6 displays the maximum stress experienced in the ROI of the mandible. In Orientation 1, which corresponds to vertical fractures, titanium plates exhibit maximum stress values ranging from 34.87 MPa to 49.81 MPa, indicating strong performance under load. Conversely, magnesium plates show lower stress levels, with values between 26.04 MPa and 50.41 MPa, suggesting that titanium may provide superior load-bearing capacity in this context. For Orientation 2, maximum stress in titanium plates varies from 29.91 MPa to 34.60 MPa, while magnesium plates display a slightly higher range of 36.35 MPa to 40.21 MPa. This suggests that, while both materials can handle stress effectively, magnesium plates may offer comparable or better performance under favorable fracture conditions. In Orientation 3, titanium plates again demonstrate higher stress values, between 29.32 MPa and 46.63 MPa, compared to magnesium plates, which range from 34.54 MPa to 41.87MPa. Figs. S26-S37 show Maximum Stress in the Mandible for Magnesium and Titanium for Type 1 and Type 2 plates.

When the performance of titanium and magnesium plates for mandibular fracture fixation, focusing on stress distribution across different fracture orientations and plate

Table 5. Maximum Deformation (mm) in the Mandible (ROI).

Orientation	Plate Thickness (mm)	Plate Type 1 (mm)	Plate Type 2 (mm)	Plate Type 1 (mm)	Plate Type 2 (mm)
		Titanium		Magnesium	
Orientation 1 Vertical Fracture	1.25	0.27932	0.22448	0.27940	0.22438
	1.5	0.27872	0.22467	0.27889	0.22458
	2.0	0.27776	0.22408	0.27798	0.22420
Orientation 2 Unfavorable Fracture	1.25	0.22247	0.22360	0.22242	0.22367
	1.5	0.22432	0.22188	0.22431	0.22200
	2.0	0.22420	0.22306	0.22420	0.22318
Orientation 3 Favorable Fracture	1.25	0.27932	0.27737	0.27901	0.27775
	1.5	0.27872	0.27676	0.27829	0.27720
	2.0	0.27776	0.27634	0.27808	0.27685

Table 6. Maximum Stress (MPa) in the Mandible (ROI).

Orientation	Plate Thickness (mm)	Plate Type 1 (MPa)	Plate Type 2 (MPa)	Plate Type 1 (MPa)	Plate Type 2 (MPa)
		Titanium		Magnesium	
Orientation 1 Vertical Fracture	1.25	49.81	42.22	50.41	27.09
	1.5	34.87	36.32	30.89	26.04
	2.0	38.36	39.22	28.36	30.55
Orientation 2 Unfavorable Fracture	1.25	34.60	40.02	30.65	36.35
	1.5	29.91	41.71	28.07	38.05
	2.0	30.89	43.93	31.12	40.21
Orientation 3 Favorable Fracture	1.25	36.99	46.63	37.94	41.87
	1.5	29.32	39.67	30.15	34.54
	2.0	32.87	39.45	26.53	35.80

thicknesses, was evaluated, Magnesium plates consistently showed lower stress, particularly in vertical and favorable fractures, with a more predictable reduction in stress as thickness increased. In contrast, titanium exhibited higher initial stress levels and inconsistent stress reduction with increasing thickness, particularly for Plate Type 2, where stress even increased at higher thicknesses. For unfavorable fractures, titanium plates saw a reduction in stress at 1.5 mm thickness, but this trend reversed at 2.0 mm. Magnesium, however, displayed a steady reduction in stress across all thicknesses, making it a more reliable material in terms of stress management. Vertical fractures produced the highest stress levels for both materials, indicating that fracture orientation plays a significant role in stress distribution. Magnesium's consistent performance suggests it is preferable in cases requiring reduced stress, such as patients with lower bone density. Titanium, though capable of withstanding higher mechanical loads, exhibited variability in stress performance, particularly in thicker plates. Overall, magnesium offers advantages for minimizing stress, while titanium may be better suited for more severe fractures requiring higher structural support.

To understand the correlation and interrelation between Plate Type 1 and Plate Type 2, we can analyze how the maximum stress (MPa) changes with different plate thicknesses and orientations in both the Titanium and Magnesium plates.

3.1.1 Titanium plates

1. Vertical Fracture: At 1.25 mm thickness, Plate Type 1 (49.81 MPa) exhibits higher stress compared to Plate Type 2 (42.22 MPa). As the thickness increased to 1.5 mm, the stress in Plate Type 1 decreased significantly to 34.87 MPa, whereas Plate Type 2 experienced a smaller reduction to 36.32 MPa. At 2.0 mm, the stress levels in Plate Type 1 increase slightly to 38.36 MPa, while Plate Type 2 also shows a slight increase to 39.22 MPa.

Plate Type 1 and Plate Type 2 generally follow a similar trend: both show reduced stress as the thickness increases from 1.25 mm to 1.5 mm, but then slightly increase at 2.0 mm. The reduction in stress is more pronounced in Plate Type 1, suggesting that it is more sensitive to changes in thickness. Plate Type 1 consistently bears more stress than Plate Type 2 at all thicknesses in vertical fractures, indicating that Plate Type 1 might be better suited for scenarios requiring higher load-bearing capacity, whereas Plate Type 2 offers lower stress at thinner dimensions.

2. Favorable Fracture: At 1.25 mm thickness, Plate Type 1 shows lower stress (34.60 MPa) compared to Plate Type 2 (40.02 MPa). Increasing the thickness to 1.5 mm results in a decrease in stress for Plate Type 1 to 29.91 MPa, while Plate Type 2 increases to 41.71 MPa. At 2.0 mm thickness, the stress of Plate Type 1 increases slightly to 30.89 MPa, while that of Plate Type 2 continues to increase to 43.93 MPa.

In favorable fractures, Plate Type 1 and Plate Type 2 displayed contrasting trends as thickness increased. While Plate Type 1 showed a decrease in stress, Plate Type 2 showed an increase, suggesting that Plate Type 2 may be less efficient in distributing stress as the thickness increases. Plate Type 1 demonstrates better stress management in favorable fractures, especially as the thickness increases, while Plate Type 2's higher stress levels suggest that it may be less suitable for such fractures unless thicker plates are necessary.

3. Unfavorable fracture: At 1.25 mm thickness, Plate Type 1 has a lower stress (36.99 MPa) than Plate Type 2 (46.63 MPa). At 1.5 mm, the stress in Plate Type 1 decreases significantly to 29.32 MPa, while Plate Type 2 also shows a reduction to 39.67 MPa. At 2.0 mm, the stress of Plate Type 1 increases to 32.87 MPa, while Plate Type 2 remains relatively stable at 39.45 MPa. Both Plate Types show a reduction in

stress as thickness increases from 1.25 mm to 1.5 mm, with a slight increase for Plate Type 1 at 2.0 mm, while Plate Type 2 remains stable. This indicates a more stable performance in Plate Type 2 with increasing thickness. Plate Type 1, which shows lower stress at thinner plates, experiences a slight increase as the thickness increases, suggesting that Plate Type 2 might offer more consistent performance across different thicknesses in unfavorable fractures.

3.1.2. Magnesium plates

1. Vertical fracture: Plate Type 1 and Plate Type 2 both showed a reduction in stress as the thickness increased, although Plate Type 2 demonstrated a slight increase at the highest thickness. The reduction in stress was more consistent for Plate Type 1. Plate Type 2 shows significantly lower stress at thinner plates but becomes less efficient at managing stress as the thickness increases, particularly at 2.0 mm, where its stress level exceeds that of Plate Type 1.

2. Favorable fracture: At 1.25 mm thickness, Plate Type 1 shows lower stress (30.65 MPa) compared to Plate Type 2 (36.35 MPa). At 1.5 mm, the stress in Plate Type 1 decreased to 28.07 MPa, while that in Plate Type 2 increased slightly to 38.05 MPa. At 2.0 mm, the stress of Plate Type 1 increased slightly to 31.12 MPa, while that of Plate Type 2 continued to rise to 40.21 MPa. Plate Type 1 and Plate Type 2 exhibit divergent trends with increasing thickness, whereas Plate Type 1 shows more consistent stress management, whereas Plate Type 2 consistently increases stress as thickness increases. Plate Type 1 is more effective in reducing stress as thickness increases, whereas Plate Type 2, although initially showing lower stress at thinner plates, becomes less effective at greater thicknesses.

3. Unfavorable fracture: At 1.25 mm thickness, Plate Type 1 has a slightly lower stress (37.94 MPa) compared to Plate Type 2 (41.87 MPa). At 1.5 mm, the stress in Plate Type 1 decreases to 30.15 MPa, while that in Plate Type 2 decreases to 34.54 MPa. At 2.0 mm, the stress of Plate Type 1 further reduces to 26.53 MPa, while that of Plate Type 2 slightly increases to 35.80 MPa.

Plate Type 1 and Plate Type 2 both show a reduction in stress as the thickness increases; however, Plate Type 2 starts to increase at 2.0 mm, whereas Plate Type 1 continues to decrease. This indicates a divergence in the performance between the two Plate Types as the thickness increases. Plate Type 1 exhibits a more reliable reduction in stress with increasing thickness, making it potentially more suitable for unfavorable fractures. Plate Type 2, which initially offers higher stress, exhibits less consistency at greater thicknesses.

Overall, it suggests that Plate Type 1 typically exhibits higher stress levels at thinner plates but benefits more from increasing thickness, especially in magnesium. Plate Type 2 tends to start with a lower stress but may increase or stabilize at higher stress levels as the thickness increases. Both Titanium and Magnesium exhibit similar trends in the behavior of Plate Types 1 and 2, with magnesium generally showing more pronounced reductions in stress across both Plate Types. The clinical implications suggest that the choice between Plate Type 1 and Plate Type 2 should be based on the specific fracture type and required load-bearing capacity. Plate Type 1 might be preferable in scenarios where the plate thickness can be increased to reduce stress, whereas Plate Type 2 could be more suitable for applications requiring lower initial stress at thinner plates, although care must be taken as the thickness increases.

3.2. Discussion

Mandibular angle fractures are among the most complex maxillofacial injuries to be managed because of the anatomical and functional characteristics of the mandible. The angle of the mandible serves as a structural junction and is subjected to significant muscular forces from the masseter, medial pterygoid, and temporalis muscles.[9-11] These forces exert considerable strain during mastication, increasing the risk of fragment displacement, particularly in unfavorable fractures where muscle pull opposes natural healing alignment. Furthermore, the mandible is continuously exposed to stress due to daily functional activities such as speech and mastication, rendering the stabilization of fractures at the angle even more critical. Given these factors, clinicians are often tasked with balancing mechanical stability with minimally invasive methods to avoid complications, making the selection of a fixation technique crucial for mandibular angle fractures.

Fracture patterns introduce an additional level of complexity. Vertical fractures, frequently resulting from direct trauma, present distinct challenges owing to the alignment of the fracture line with the direction of bite forces, thereby complicating stabilization.[12] In unfavorable fractures, the fracture pattern induces displacement of bone fragments owing to muscle action, increasing the risk of improper healing without rigid fixation. Conversely, favorable fractures exhibit natural alignment that facilitates the stabilization of bone fragments under muscle tension, thus reducing the need for extensive surgical intervention. However, even in these instances, complications may arise because of variability in fracture morphology and the individual's physiological response to trauma. Therefore, a comprehensive understanding of these fracture patterns is crucial to selecting the most appropriate fixation method and material for optimal patient outcomes.[3,13,14]

The treatment of mandibular angle fractures has evolved significantly over the years, with the introduction of plate osteosynthesis representing a major advancement. Mini plates are particularly efficacious in cases where the fracture line is favorable because they allow for functional loading of the mandible with minimal risk of displacement. However, in cases of unfavorable fractures or vertical fractures, where the displacement is more significant, a single mini plate may not provide sufficient stability. In such situations, dual plating or the use of larger reconstruction plates is often necessary to ensure rigid fixation and proper healing. Dual plating involves placing one plate along the superior border and another along the inferior border of the mandible, providing a broader area of fixation and preventing rotational forces that could lead to malunion.[14-17]

The material of the plates also plays a pivotal role in fixation success. Titanium has become the gold standard for mandibular fracture fixation owing to its strength, biocompatibility, and resistance to corrosion.[18] Titanium plates provide excellent rigidity, particularly in cases where maximum load-bearing capacity is required, such as in unfavorable fractures. However, there is a growing interest in the utilization of biodegradable materials, such as magnesium-based plates, which can provide sufficient initial stability while gradually resorbing over time. This eliminated the need for a second surgery to remove the plates, thereby reducing the overall treatment burden on the patient.[19,20] Although biodegradable plates show promise, their current strength and performance may not yet be equal to that of titanium, particularly in high-stress fractures. Another recent advancement is the utilization of 3D plates, which are engineered to distribute forces more uniformly across the fracture site.[21-24] These plates provide enhanced stability by mitigating the bending and torsional forces acting on the fracture fragments, rendering them particularly efficacious for complex or comminuted fractures. However, the application of 3D plates necessitates more precise planning and is often reserved for cases in which standard plates may not provide adequate fixation.[25-27]

The present FEA study investigated the biomechanical performance of different plate materials and configurations in mandibular angle fractures, including vertical, favorable, and unfavorable fracture patterns. The results of this study align with the established understanding that plate material and thickness significantly affect the stress distribution and deformation in the mandible. Specifically, titanium plates demonstrated superior mechanical stability across all fracture patterns, particularly in unfavorable fractures, where the stresses were the highest. The rigidity of titanium plates renders them well-suited for managing fractures with significant displacement, where muscle forces exert considerable strain on the fixation system. However, the study also revealed that magnesium plates, particularly in thicker configurations, could reduce stress in certain fracture patterns, indicating their potential for managing fractures in patients with less demanding mechanical requirements.

In vertical fractures, where the fracture line aligns with the forces of mastication, titanium plates consistently provide the highest resistance to deformation, offering stable fixation even in thin-plate configurations. Magnesium plates, while demonstrating lower stress levels, exhibited increased deformation compared to titanium, indicating that, while magnesium may offer benefits in terms of stress reduction, it may not be as effective in resisting deformation under high mechanical loads. For favorable fractures, both titanium and magnesium performed adequately, with magnesium plates demonstrating lower stress values, particularly in thicker configurations. This suggests that magnesium plates may be a viable alternative for less mechanically demanding fractures, offering the additional benefit of resorption without compromising stability.

For unfavorable fractures, where muscle forces tend to displace fracture fragments, rigid fixation is paramount. Our findings suggest that while magnesium plates offer promise, titanium remains the preferred material for these fractures because of its superior rigidity and ability to resist deformation. The results of our study underscore the importance of selecting the appropriate material and plate configuration based on specific fracture patterns, patient factors, and mechanical demands. While magnesium plates may offer advantages in terms of resorption and reduced stress, titanium remains the gold standard, particularly for fractures requiring maximum load-bearing capacity.

The observed trends in stress distribution between Plate Type 1 and Plate Type 2 across different thicknesses and fracture orientations can be attributed to several factors that are generally related to material properties, plate design, and biomechanical considerations.

3.2.1 Material properties

The difference in the elastic modulus between Titanium and Magnesium influences the stress distribution across the plates. Titanium, which is stiffer, tends to bear more stress, especially at thinner thicknesses, whereas magnesium, which is less stiff, distributes stress differently, leading to varying trends as the thickness increases. The yield strength of the materials affects how they handle stress before deformation. The higher yield strength of titanium allows it to maintain higher stress levels without permanent deformation, which could explain why Plate Type 1 shows higher stress at thinner dimensions. In contrast, the lower yield strength of Mg might lead to different stress distribution patterns as the plate thickness changes.

3.2.2 Plate design and geometry

As plate thickness increased, the cross-sectional area also increased, which generally reduced the stress concentration by distributing the load over a larger area. This is why both Plate Types tend to exhibit lower stress in thicker dimensions. The specific design of plate types 1 and 2 could influence how they interact with the surrounding bone tissue. Plate Type 1 may have a design that concentrates stress more effectively, leading to higher stress levels at thinner dimensions, whereas Plate Type 2 might be designed to distribute stress more evenly, particularly at thinner plates.

3.2.3 Biomechanical interaction

The manner in which the plates interact with the fractured bone plays a significant role. Plate Type 1 might be better suited to handle direct loads, resulting in higher stress concentrations, particularly in vertical fractures where load transmission is more direct. Plate Type 2, on the other hand, can be designed to distribute these loads more evenly and reduce stress, particularly under less direct load conditions such as favorable fractures. Different fracture orientations create different load paths. Vertical fractures usually result in more direct load transmission through the plate, whereas favorable and unfavorable fractures distribute the load differently. This leads to varied stress levels, depending on how well the plate can accommodate these load paths.

3.2.4 Thickness and structural integrity

As the thickness of the plate increases, its structural integrity improves, leading to better load distribution and lower stress concentrations. This was observed as a general trend in both Plate Types, where the stress decreased as the thickness increased. However, the specific design and material properties of each plate type influence the decrease or stabilization of stress at different thickness levels. Thicker plates generally offer more stability and rigidity, which can reduce the likelihood of stress concentration at any single point. This could explain the reduction in stress for both Plate Types as the thickness increased, particularly in more complex fracture scenarios, such as unfavorable fractures.

Generally, Plate Type 1 typically shows higher stress at thinner dimensions and more significant reductions in stress with increasing thickness, while Plate Type 2 may show lower initial stress but varying performance as thickness increases. Understanding these factors helps in choosing the appropriate plate type for specific clinical scenarios and balancing between initial stress management and the effects of increased thickness.

4. Conclusions

This study provides a comprehensive analysis of stress distribution in titanium and magnesium mini-plates used for mandibular fracture fixation, highlighting significant implications for clinical practice. The results indicate that titanium plates exhibit higher stress levels, particularly in thinner dimensions, suggesting a potential risk of stress-related complications. Conversely, magnesium plates consistently demonstrate lower stress levels, particularly in favorable fractures, indicating a more stable mechanical environment, especially for Plate Type 1. The behavior of the plates varies with thickness; while increasing thickness generally reduces stress, titanium plates show unpredictable stress responses, particularly in Plate Type 2, where stress may increase with thickness. This variability underscores the need for careful consideration of the plate selection based on specific fracture orientations. Our findings also revealed that fracture type significantly influences stress distribution, with vertical fractures inducing the highest stress levels, warranting a robust fixation solution. The predictable performance of magnesium plates suggests that they may be advantageous for patients with lower bone density or for those at risk of stress-related complications. Overall, this analysis provides valuable insights into the biomechanical behavior of different plate materials, guiding surgeons in making informed decisions tailored to the individual characteristics of mandibular fractures. Future research should focus on the long-term clinical outcomes associated with these materials to validate their effectiveness and reliability in fracture management.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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