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Optimizing Fixation in Mandibular Angle Fractures: A Biomechanical Comparison of Single, Double, and 3D Miniplate Systems using Finite Element Analysis

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Abstract; This study evaluates the stress distribution on miniplates and bone and the displacement of fractured segments in mandibular angle fractures using Finite Element Analysis (FEA). Three fixation methods were analyzed: a single straight titanium miniplate on the superior border, two straight titanium miniplates placed on the superior and inferior borders, and a 3D miniplate on the lateral surface. A 3D mandibular model was generated using CT and CBCT imaging, and occlusal forces were applied in a vertically downward direction. Stress distribution was assessed through von Mises stress analysis, and maximum displacement of fracture segments was compared across fixation methods.

The results showed that the highest von Mises stress on miniplates was observed in the 3D plate fixation model, reaching 673 MPa at 1000N, exceeding the titanium yield limit, while the single and two-plate models remained within safe limits at 195.17 MPa and 367.1 MPa, respectively. The highest stress on screws and screw holes was also recorded in the 3D plate model, with 415.72 MPa on screws and 52.15 MPa on screw holes, indicating a higher risk of deformation. Total deformation analysis showed that the inferior border exhibited the maximum displacement in all models, with the highest displacement of 0.052 mm observed in the two-plate model.

Within the study's limitations, the findings suggest that a single miniplate on the superior border provides adequate stability while being surgically simpler. FEA offers valuable insights into biomechanical behavior, aiding in the optimization of fixation techniques before clinical trials.

Keywords: *Finite Element Analysis, Mandibular Angle Fracture, Miniplate Fixation.*

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I. INTRODUCTION

Mandibular fractures constitute 19–40% of all facial fractures due to their prominence and mobility, with mandibular angle fractures accounting for 12–30%. These fractures are biomechanically vulnerable due to a thinner cross-sectional area and the presence of third molars(1,2).

The primary fixation methods include single, two-plate, and 3D miniplate systems, each with its biomechanical advantages and challenges(3). The Champy technique, widely used for single miniplate fixation, has been questioned due to its inability to fully stabilize the fracture, leading to potential complications such as malocclusion and non-union(4,5). Two-plate and 3D miniplate systems have been proposed as alternatives to improve stability, yet their effectiveness remains debated(6).

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Finite Element Analysis (FEA) is a computational method that allows for the precise simulation of mechanical behavior under different loading conditions. Compared to traditional mechanical testing, FEA provides a detailed assessment of stress distribution and deformation patterns in bone-plate systems(7,8).

This study aims to compare the biomechanical performance of single, two-plate, and 3D miniplate fixation systems in mandibular angle fractures using FEA. By analyzing stress distribution and displacement, this research provides objective insights into the optimal fixation method for clinical application.

II. MATERIALS AND METHODOLOGY

This finite element analysis (FEA) study was conducted at the Department of Oral and Maxillofacial Surgery, Christian Dental College, Ludhiana. A personal computer with an Intel Core i5 processor and 8GB RAM was used for computations. The software employed included ANSYS Mechanical 2022 R1 for meshing and analysis and SpaceClaim for CAD modeling. Dimensional data for miniplates and screws were sourced from a standard manufacturer's catalog. CT and CBCT scans of human mandibles were utilized for modeling the bone structure. The material properties assigned in the study were based on standard values, with bone having a Young's modulus of 13,400 MPa and Poisson's ratio of 0.30, while titanium alloy had a Young's modulus of 110,000 MPa and Poisson's ratio of 0.33(9).

Two types of miniplates were analyzed: a four-hole straight titanium miniplate and a four-hole 3D titanium miniplate. The specifications of these plates and screws are detailed in Table 1. The masticatory muscle forces were applied based on existing literature, with force magnitudes and directional vectors as summarized in Table 2(10).

Table 1 Miniplate and Screw Dimensions

Type	Length (mm)	Thickness (mm)	Hole Diameter (mm)
Straight Miniplate	20	1.5	2.3 (Inner), 4.2 (Outer)
3D Miniplate	10 (between holes)	1.5	2.3 (Inner), 4.2 (Outer)
Screws	6	-	2 (Thread), 2.3 (Head)

Table 2 Muscle Force Magnitudes and Direction Vectors

Muscle	Magnitude (N)	Right X/Y/Z	Left X/Y/Z
Masseter	190.4	-0.207/0.884/0.419	0.207/0.884/0.419
Temporalis	95.6	-0.222/0.837/-0.50	0.222/0.837/-0.50
Lateral Pterygoid	28.7	0.761/0.074/0.645	-0.761/0.074/0.645
Medial Pterygoid	174.8	0.486/0.791/0.373	0.486/0.791/0.373

The methodology consisted of three primary stages: pre-processing, processing, and solution. In the pre-processing stage, CT/CBCT scans were converted into STL format and imported into ANSYS for geometric modeling. A simulated mandibular angle fracture was created with inter-fragmentary bone contact. Three plating systems were tested: single miniplate fixation at the superior border, two miniplate fixation at the superior and inferior borders, and 3D miniplate fixation on the lateral surface of the mandible. The miniplates and screws were positioned and assigned bonded and frictional contacts to simulate real-world conditions.

During the processing stage, hexahedral meshing was applied, with refinements near the interfaces for accuracy. The total number of elements varied across models, with Model 1 having 396,267 elements, Model 2 having 412,207 elements, and Model 3 containing 401,225 elements. Boundary conditions were established by applying occlusal forces in the reverse Z-axis, ranging from 62.8N to 1000N in 100N increments. The bilateral condyles were constrained to prevent displacement, and muscle forces were simulated based on previously published biomechanical data.

III. RESULTS

➢ *Stress Distribution on Miniplates*

Finite element analysis was used to evaluate stress distribution on miniplates, screws, and screw holes, as well as the total deformation around the fracture line. The study compared three models:

- *Model 1: Single miniplate on the superior border.*
- *Model 2: Two miniplates on the superior and inferior borders.*
- *Model 3: 3D miniplate on the lateral border.*

Fixed support was applied at the bilateral condylar region, and occlusal forces ranging from 100N to 1000N were applied in the reverse Z-axis direction, along with respective masticatory muscle forces.

At occlusal forces ranging from 62.8N to 1000N, the maximum von Mises stress (VMS) on the miniplates was concentrated near the fracture line in all models. Model 3 showed the highest stress concentration (25.18 MPa to 673 MPa), exceeding titanium's yield limit at forces beyond 700N. In contrast, Model 1 and Model 2 remained within safe limits under normal occlusal loads (table 3).

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Table 3 Maximum Von Mises Stress (MPa) on Miniplates

Force (N)	Model 1	Model 2	Model 3
1000	195.17	367.1	673.13
900	166.8	305.73	605.81
800	148.3	270.40	538.50
700	129.78	236.6	469.0
600	111.24	203.82	402.2
500	92.5	169.55	337.5
400	74.0	135.20	269.2
300	55.5	101.19	201.9
200	37.0	67.94	133.0
100	22.7	34.34	69.5
62.8	11.64	21.33	42.27

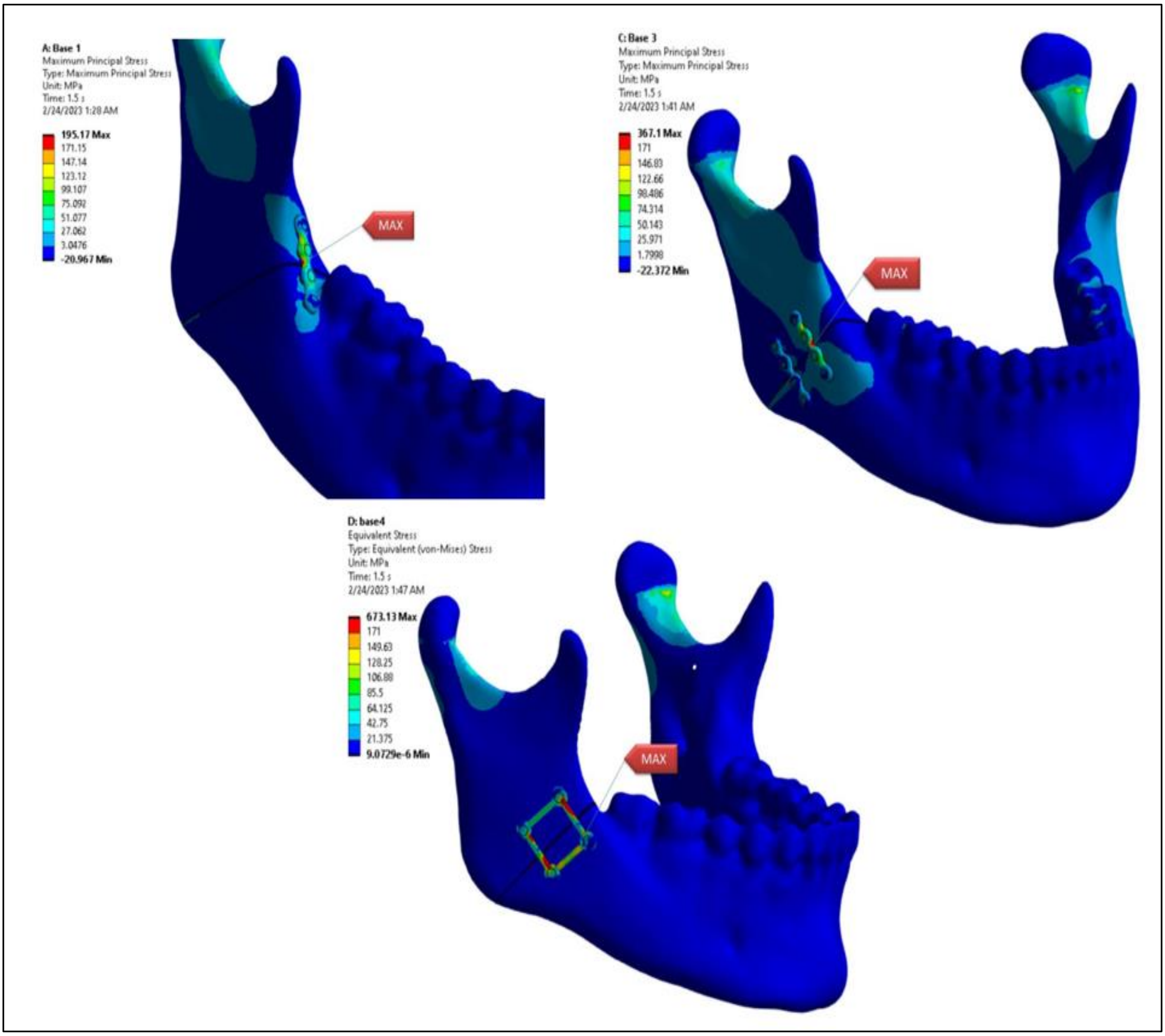

Fig 1 Von Mises Stress on Miniplates

➢ *Stress Distribution on Screws*

The highest stress concentration on screws was found near the mesial segment close to the fracture line. Model 3 experienced the highest stress (26.1 MPa to 415.72 MPa), reaching the yielding point of titanium at 1000N. Model 1 and Model 2 remained within acceptable stress limits (table 4).

Table 4 Maximum von Mises Stress (MPa) on Screws

Force (N)	Model 1	Model 2	Model 3
1000	105.3	198.2	415.72
900	94.5	178.38	374.14
800	84.0	157.6	331.2
700	72.1	139.3	292.6
600	63.6	118.92	249.43
500	52.65	98.0	207.86
400	42.24	78.4	164.4
300	31.8	59.1	124.2
200	21.06	39.64	83.14
100	10.3	19.60	39.14
62.8	6.4	12.43	26.10

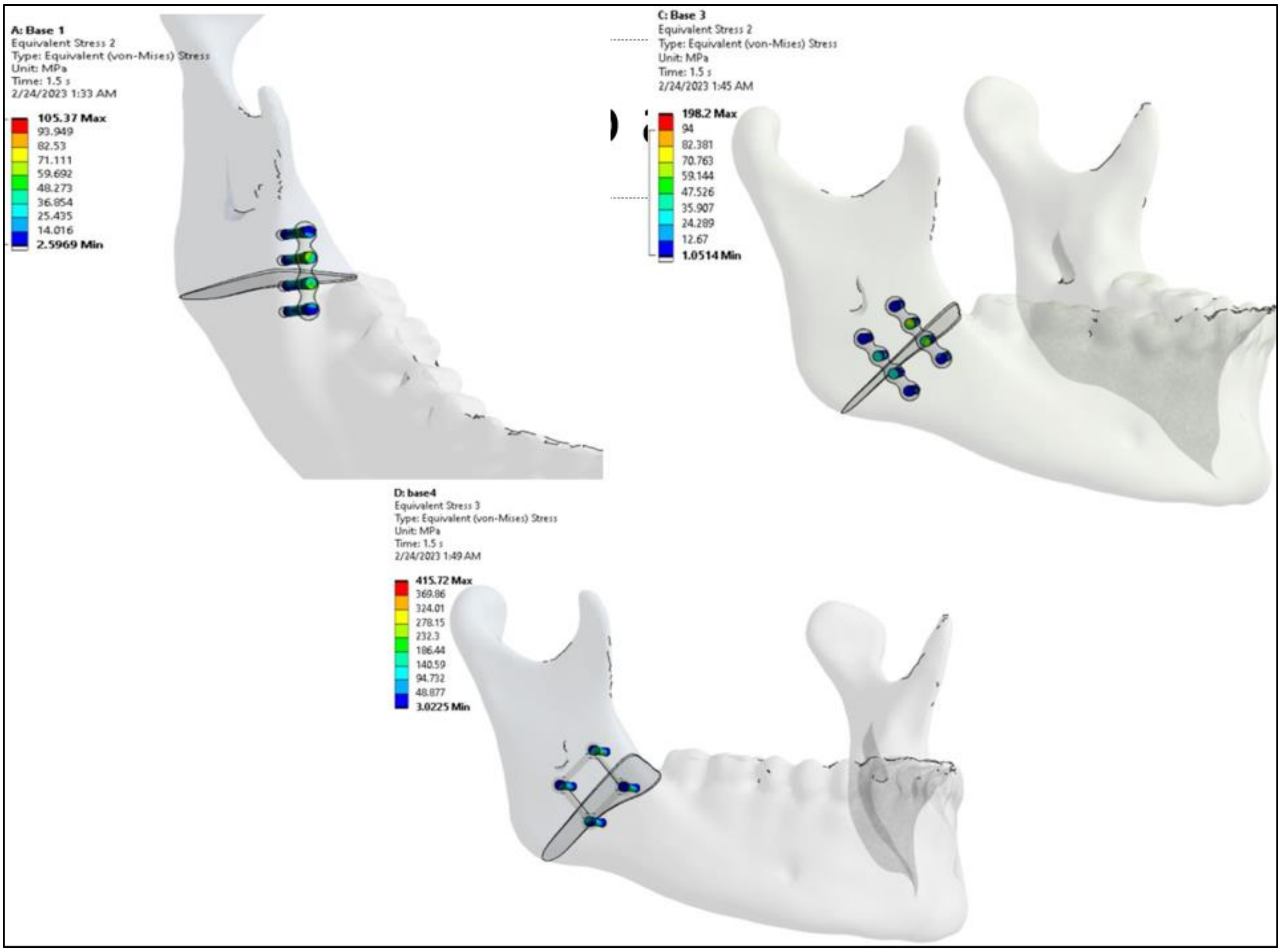

Fig 2 Von Mises Stress on Screws

➤ *Stress Distribution on Screw Holes*

Analysis of stress on screw holes indicated the highest VMS near the anterior-most screw hole in Model 1 and at the upper screw hole in Models 2 and 3. Model 3 exceeded the yield strength of bone (51 MPa) at 1000N occlusal forces, indicating a higher risk of failure (table 5).

Table 5 Maximum von Mises Stress (MPa) on Screw Holes

Force (N)	Model 1	Model 2	Model 3
1000	47.14	32.28	52.15
500	24.62	18.13	28.15
100	6.23	5.12	8.32

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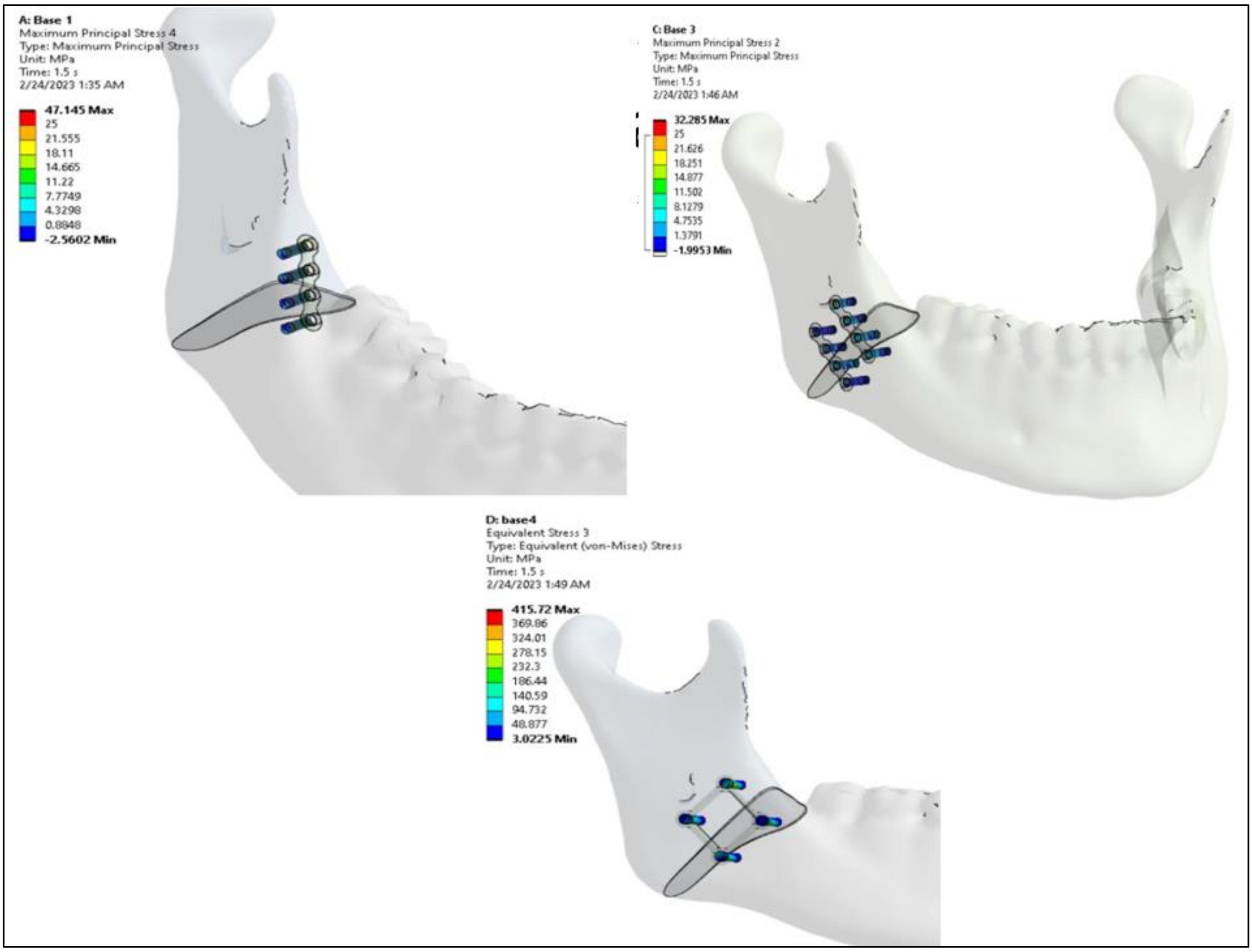

Fig 3 Von Mises Stress on Screws Holes

➢ *Total Deformation Around the Fracture Line*

Total deformation (TD) was evaluated under 100N occlusal force to determine post-operative stability. The maximum TD was observed at the inferior border in all models, with Model 2 showing the highest displacement (0.052 mm). The results indicate that all models remained within the acceptable range for primary bone healing (0.15 mm) (table 6).

Table 6 Total Deformation Around the Fracture Line (mm) at 100N

Location	Model 1	Model 2	Model 3
Superior border	0.041	0.043	0.047
Lateral border	0.042	0.044	0.041
Inferior border	0.048	0.052	0.050
Medial border	0.042	0.045	0.048

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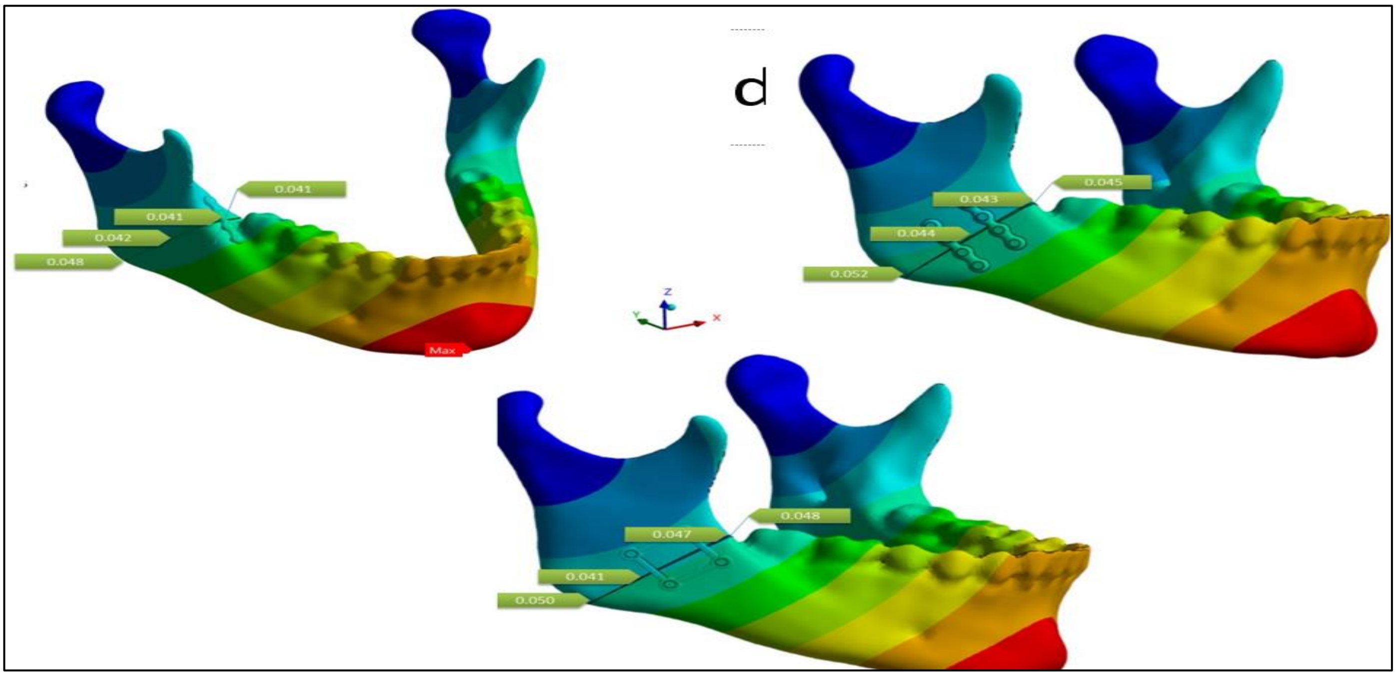

Fig 4 Total Deformation Around the Fracture Line at 100n Occlusal Force

IV. SUMMARY OF FINDINGS

- *Model 3 exhibited the highest stress values, exceeding titanium's yield strength under high occlusal loads, indicating potential failure risks.*
- *Model 2 demonstrated moderate stress values but had the highest total deformation, suggesting reduced stability.*
- *Model 1 showed the lowest stress values and remained within acceptable limits under all loading conditions, making it the most stable fixation system.*

These results highlight the importance of selecting an appropriate plating system based on biomechanical performance and load-bearing capacity.

V. DISCUSSION

This study employed finite element analysis (FEA) to evaluate stress distribution and displacement patterns in single, two-plate, and 3D miniplate fixation systems. The stress patterns on plates, screws, and screw holes were analyzed under simulated occlusal forces. Additionally, the total deformation of the mandible was assessed to determine fracture segment stability during the healing period. Excessive mobility at the fracture site can lead to malunion, infection, and delayed healing, emphasizing the need for biomechanical evaluation. To create an accurate mandibular model, CT and CBCT images were reformatted and processed using SpaceClaim software. The miniplates used in this study were designed based on popular manufacturer specifications. The bone was considered isotropic, homogeneous, and linearly elastic to simplify calculations while maintaining clinically relevant accuracy. Various studies suggest that such simplifications do not significantly affect the practical outcomes of FEA models(7,8,11).

The highest von Mises stresses (VMS) were observed near the superior aspect of plating systems, close to the fracture line in all models. Model 3 (3D miniplate) exhibited the highest stress (673 MPa at 1000N), surpassing the titanium yield limit (450–500 MPa) at forces above 700N, indicating potential risk of plate deformation. In contrast, Model 1 (single miniplate) and Model 2 (two miniplates) remained within safe stress limits, suggesting better biomechanical stability under normal occlusal forces. The highest stress on screws was recorded on the mesial segment near the fracture line, with Model 3 experiencing the maximum VMS (415.72 MPa at 1000N), exceeding titanium's yield limit. Model 1 and Model 2 showed significantly lower stress values, staying within acceptable limits. The stress on screw holes was highest at the anterior-most screw hole in Model 1, and at the upper screw hole in Models 2 and 3. Importantly, Model 3 exceeded the bone yield strength (51 MPa), increasing the risk of bone resorption and failure.

Total deformation (TD) analysis revealed that all models maintained displacement within the acceptable range for primary bone healing (0.15mm). The highest deformation was observed at the inferior border of the fracture line, with Model 2 showing the most significant movement (0.052 mm), suggesting slightly reduced stability compared to the other models. This study aligns with existing biomechanical research on mandibular fracture fixation. Champy et al. (1978) introduced the single miniplate technique based on the ideal line of osteosynthesis, while Levy et al. (1991) (12) and AO/ASIF (1995) advocated two-plate fixation to restore compression trajectories. The 3D miniplate system, designed to improve resistance to bending and torsional forces, has shown higher stress concentrations in clinical studies, leading to increased post-operative complications such as occlusal changes and plate deformation.

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Clinical research by Zix et al. 2007(13) reported a higher incidence of infection and screw loosening (10%) in 3D plates compared to straight miniplates. Similarly, Siddiqui et al. in 2006(14) and Vitkos et al. in 2022(15) found no significant differences in complications between single and two-plate systems, though two-plate fixation was associated with higher rates of wound dehiscence and hardware failure.

As with all FEA-based studies, this research has inherent limitations. The model was derived from a single patient's CT data, and repeating the study on multiple patient datasets would strengthen findings. Additionally, while material properties were assigned accurately, real bone exhibits anisotropic and heterogeneous behavior, which was simplified in this study. Although FEA provides a detailed biomechanical comparison, validation through clinical trials and direct patient outcomes remains necessary to fully integrate these findings into surgical practice.

VI. CONCLUSION

Findings from this study suggest that single and two-miniplate fixation systems are superior to 3D plating in terms of biomechanical stability and stress distribution. 3D plates exhibited higher stress values, crossing material yield limits at high occlusal loads, indicating potential risks of plate deformation, screw failure, and bone resorption. The results support the continued use of single and two-plate fixation techniques, with further clinical validation needed to refine treatment protocols for mandibular angle fractures.

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