The Scientific Temper (2024) Vol. 15 (1): 1602-1612
Doi: 10.58414/SCIENTIFICTEMPER.2024.15.1.06
E-ISSN: 2231-6396, ISSN: 0976-8653
https://scientifictemper.com/

RESEARCH ARTICLE

Evaluation of stability of fixation using conventional miniplate osteosynthesis in comminuted and non-comminuted Le Fort I, II, III fractures – A dynamic finite element analysis

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Abstract

Purpose: The purpose of the present study was to evaluate and compare the stability of fixation using conventional miniplate osteosynthesis in comminuted and non-comminuted Le Fort I, II, and III fractures in open and closed jaw movements under masticatory loading conditions.

Materials and Methods: About 23 dimensional models of comminuted and non-comminuted Le Fort I, II, and II with traditional miniplate fixation were simulated virtually using a CT scan of the patient and analyzed using ANSYS Workbench 2020 R1 software. The dynamic finite element method was applied by the simulation of the forces of the muscles of mastication upon the fractured midface. The von Mises stress was analyzed and collated for each model; thereby, the stability of conventional miniplate fixation was interpreted.

Results: The von Mises stress over the regions of fixation were compared and the tabulated data was interpreted. Considerable von Mises stress was generated on the bone and deformation over the hardware was noted on the pyriform rim in the Le Fort I model, infraorbital rim in the Le Fort II model, and frontonasal region in the Le Fort III model in the closing phase of jaw movement.

Conclusion: The findings implicated that the biomechanical stability of conventional miniplate osteosynthesis is insufficient to secure the midface fractured bone under masticatory load.

Keywords: Finite element analysis, Computer assisted three-dimensional modeling, Conventional miniplate, Rigid fixation, Midface fractures, Trauma.

Introduction

The facial skeleton is connected with the cranial vault and the cranial base is divided for convenience into three parts, the upper third of the facial skeleton which is the part of the cranial vault and comprises of frontal bone, the middle third comprising of central midfacial bones; the maxilla, the nasoethmoid, and lateral midfacial bone zygoma, and the lower third comprising of rigid bone mandible, with its condylar articulation to base of skull. Understanding the biomechanics in midface trauma helps in the management of injuries with a low complication rate. Curtailing the osteosynthesis material to a minimum necessary for bone healing is essential from an economic and biological viewpoint. The precise nature of injury to the mid-facial region is determined by the degree of force and the resistance to the force offered by the craniofacial bones and associated muscles. The facial region in physiological states is susceptible to forces produced by the masticatory muscles and the occlusion stress that is supported by the teeth and dissipated by the facial buttresses. (Crespo Reinoso P,2021). Fractures of the mid-face can generally be divided into three broad categories viz. Lower mid-face fracture (Le Fort I fracture), pyramidal fracture (Le Fort II fracture) and High-level fracture (Le Fort III fracture).

By projecting the overlaying soft tissues that determine facial height and width, buttresses define the face's contour

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How to cite this article: Gandhi, S., Asnani, U., Natarajan, S., Rao, C., Agrawal, R. (2024). Evaluation of stability of fixation using conventional miniplate osteosynthesis in comminuted and non-comminuted Le Fort I, II, III fractures – A dynamic finite element analysis. The Scientific Temper, **15**(1):1602-1612.

Doi: 10.58414/SCIENTIFICTEMPER.2024.15.1.06

Source of support: Nil

Conflict of interest: None.

Received: 25/01/2024 **Accepted:** 20/02/2024 **Published** : 15/03/2024

by supporting the face's functional units and serving as a framework for the protection of essential organs including the eyes, brain, airway, and chewing apparatus. The posteroinferior displacement of the fractured segment frequently accompanies the mid-face fracture. The reason for this displacement is considered two-fold owing to the downward slope of the cranial base and the pull of the muscles attached to the posterior part of the maxilla.

Clinically, there has been questionable stability achieved under compressive loading after fixation in high-velocity trauma, leading to the following patterns of injuries in the midface:

- Variations of Le Fort I, II, and III fractures.
- Gross comminution along the buttresses.
- Loss of bone pieces into airspaces.
- Lack of enough bone along the buttresses to anchor the hardware.
- When subjected to muscular forces, this compromised fixation can lead to failure of fixation, causing downward and backward displacement of the fixed fragment, further leading to contour deformities and anterior open bite. The treatment of such fractures entails open reduction and internal fixation (ORIF) (plate and screw fixation) over established buttresses that transmit masticatory forces along the trajectories. Consequently, the decision of appropriate hardware, its position, type and material in the treatment planning of midface fractures are significantly important. To guide the surgeon to improve the fixation using ORIF, it is of utmost importance to contemplate the biomechanical behavior of midfacial bones under load-bearing conditions of mastication thereby improving the functional outcome. It is believed that the midface absorbs the occlusal load in an uneven manner. The zygomaticomaxillary buttress taking the largest amount of stress; the pterygomaxillary buttress receives tension and not compression loads hence not having a reinforcing function. As mentioned earlier, the occlusal load and muscle activity have a noteworthy effect on the midface skeleton. The maximum bite force ranges from 15.7 to 4341.4 N, depending on the dentition, age, sex, measurement method, and measured area. Pain, inflammation, and trismus produced by trauma and surgery alters the chewing forces decreasing it up to 31% of its total force at the first week and up to a 58% 6 weeks after the surgical intervention. The pattern of fractures in the midface is dependent on the location, direction, and magnitude of the force, as well as the surface and consistency of the object; facial bones present different levels of fracture tolerance, mainly determined by their thickness, density, and contiguity to air cavities. Finite element analysis allows to elucidate biomechanical variables such as displacement, tension, and stress on buttresses to analyze and refute some classical theories (Crespo Reinoso P,2021). Finite element analysis (FEA) is a method used to analyze stresses and strains in complex mechanical systems. It enables the mathematical conversion and analysis of the mechanical properties of a geometric object (Lisiak-Myszke M, 2020).

The rationale of this study was to evaluate the stability offered by conventional miniplate osteosynthesis under dynamic loading which will help to revisit the traditional philosophy of open reduction internal fixation (ORIF) and also help design new fixation hardware which may work in cases with comminution or in cases with loss of bone along the buttresses.

Materials and Methods

This was an *in-vitro* three-dimensional (3D) dynamic finite element analysis study. The study was conducted at the Department of Oral and Maxillofacial Surgery and the Department of Mechanical Engineering for a period of 18 months from March 2021- November 2022. The institutional ethics committee approval was effected. Computed tomography (CT) of an intact adult mid face was included in the study. The following materials were used in the study (Tables 1 and 2):

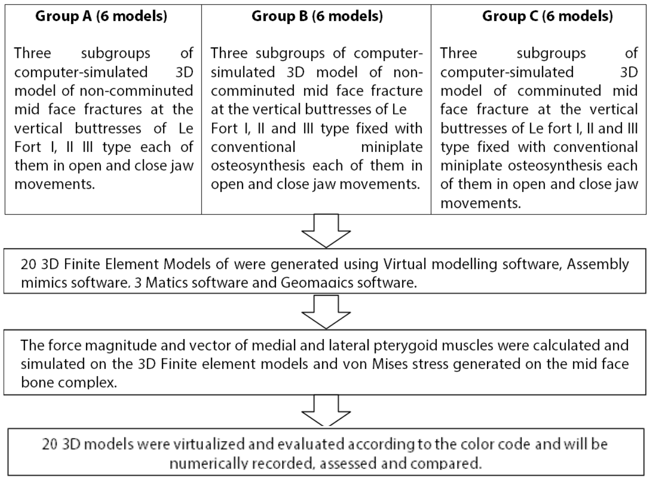
- A CT scan of an intact adult male mid-facial skull was used to make computer-simulated 3D models.
- Four-hole titanium miniplate without gap (width -2 mm, length- 29 mm)
- Four-hole 'L' shaped titanium miniplate (width- 2 mm with 1-mm profile)

Table 1: shows Von Mises stress on computer-simulated 3D model of anatomical unfractured mid-face skull with opening jaw movement.

Anatomic region	*Open jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	0.003	0.005
Pyriform rim	0.0038	0.0052
Infraorbital rim	0.0068	0.0033
Frontozygomatic suture	0.0063	0.0063
Frontonasal suture	0.018	
Zygomatic arch	0.017	0.0095

Table 2: shows Von Mises stress on computer-simulated 3D model of anatomical unfractured mid-face skull with closing jaw movement.

Anatomic region	*Close jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	5.356	2.32
Pyriform rim	0.496	1.844
Infraorbital rim	1.6	1.812
Frontozygomatic suture	3.23	4.775
Frontonasal suture	3.8	
Zygomatic arch	6.82	7.43



Group A (6 models)	Group B (6 models)	Group C (6 models)
Three subgroups of computer-simulated 3D model of non-comminuted mid face fractures at the vertical buttresses of Le Fort I, II III type each of them in open and close jaw movements.	Three subgroups of computer-simulated 3D model of non-comminuted mid face fracture at the vertical buttresses of Le Fort I, II and III type fixed with conventional miniplate osteosynthesis each of them in open and close jaw movements.	Three subgroups of computer-simulated 3D model of comminuted mid face fracture at the vertical buttresses of Le fort I, II and III type fixed with conventional miniplate osteosynthesis each of them in open and close jaw movements.

20 3D Finite Element Models of were generated using Virtual modelling software, Assembly mimics software. 3 Matics software and Geomagics software.

The force magnitude and vector of medial and lateral pterygoid muscles were calculated and simulated on the 3D Finite element models and von Mises stress generated on the mid face bone complex.

20 3D models were virtualized and evaluated according to the color code and will be numerically recorded, assessed and compared.

Flowchart 1: Depicting the segregation of models into groups and and models

- Four hole ‘Y’ shaped titanium miniplate
- Titanium screws (width- 2 mm, length- 6 and 9 mm)
- 3 D Slicer
- Fusion 360 software- plate and screw fabrication
- ANSYS Workbench 2020 R1 software- Dynamic finite element analysis
- Computer-simulated 3D models of midface at Le Fort I, Le Fort II and Le Fort III levels with and without titanium mini plates and screws using Rhino software.

Normal models (Flowchart 1):

- Model 1O (in open jaw)
- Model 2C (in close jaw)
- groups – A, B, C of 6 models each showing fractured mid-face at Le Fort I, II and III levels.

Finite Element Analysis was done using Following Steps (Flowchart 2)

- Designing of the 3D models
- Generating the volumetric Mesh (no. of nodes: 388439; no. of elements: 284242)
- Importing models in ANSYS software
- Assigning necessary material properties
- Assigning boundary conditions
- Assigning loading conditions
- Analyzing stage

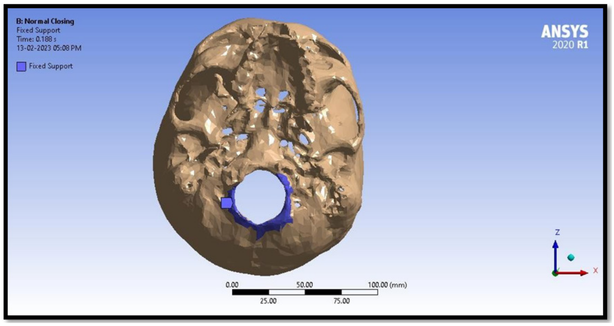


Figure 1: Depicts the boundary condition applied at the occipital condyles.

Boundary Condition

Finite elements at the occipital condyles were constrained and considered as the boundary. In all the models, the boundary condition was applied at the occipital condyles and solved. A complete unilateral mastication cycle with the right molars was simulated by applying the forces of the masticatory muscles. These forces were imposed as external loads, distributed over the insertion area of each muscle (Figure 1).

Loading Conditions

The opening and closing forces of the jaws during one masticatory cycle were simulated by the values of the amount of force exerted by the masticatory muscles with respect to time. The graphical representations depicting the amount of force with respect to time during opening and closing from Commisso *et al,* 2015 were interpreted (Table 3). Ipsilateral force values of the masticatory muscles were considered as the right side. Contralateral force values of the masticatory muscles were considered as the left side (Figures 2 and 3).

Analyzing Stage

The ANSYS Workbench 2020 R1 software solved the problem equation of stresses in the bone and the hardware with respect to time after the application of forces on the models. The results after force application were represented in the form of contour plots of von Mises stress (Figures 4 and 5).

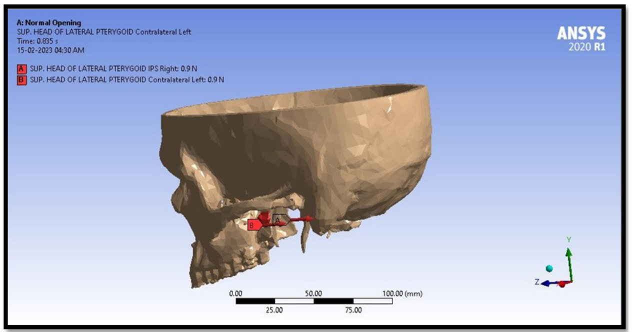


Figure 2: Depicts the origin and direction of vector of the jaw opening muscle implying the loading condition applied.

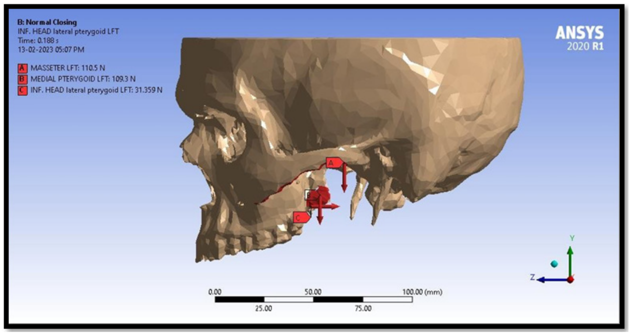
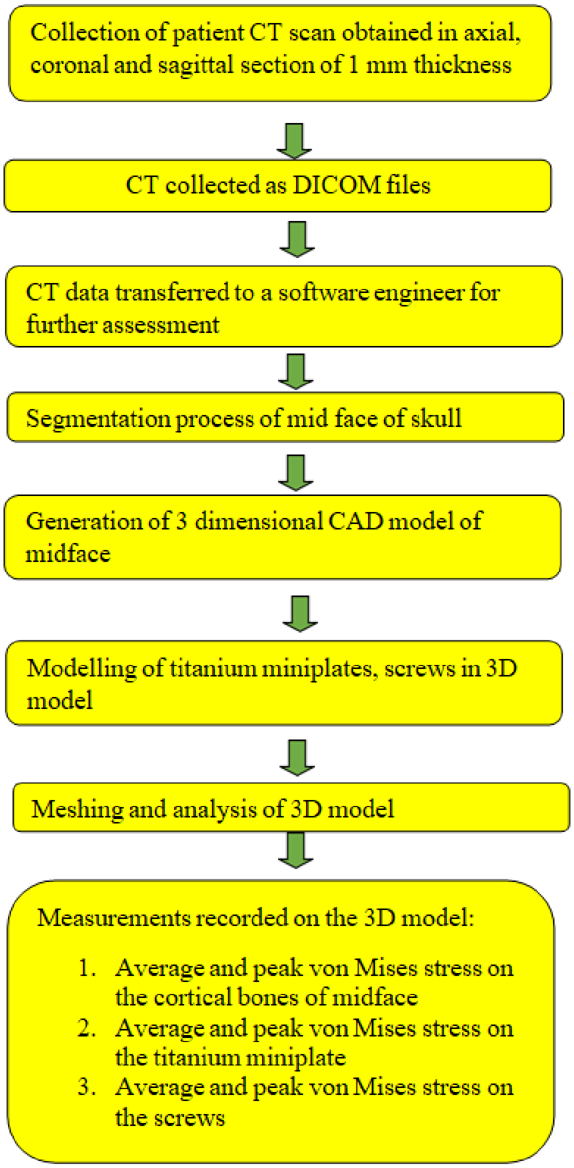


Figure 3: Depicts the origin and direction of vector of the jaw closing muscles implying the loading conditions applied.



Flowchart 2: depicting the methodology of the study

Table 3: Magnitude of amount of maximum masticatory muscles during opening and closing. [Commisso et al, 2014]

	Name	*Force max Magnitude (n)*	*Direction*
Closing	Masseter	136	Downwards
	Medial pterygoid	174.8	Downwards
	Inferior lateral Pterygoid	66.9	Inwards
Opening	Superior lateral pterygoid	28.8	Inwards

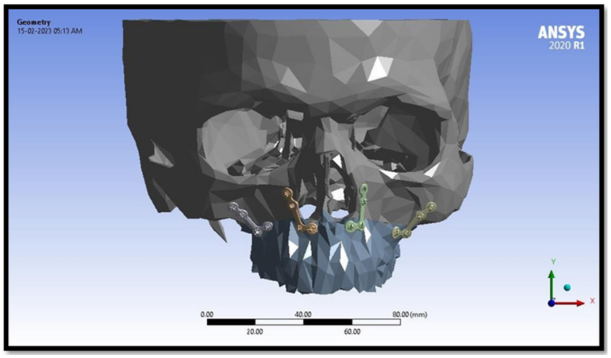


Figure 4: Depict the 3D model of non-comminuted Le Fort I fracture with miniplate osteosynthesis in the frontal view

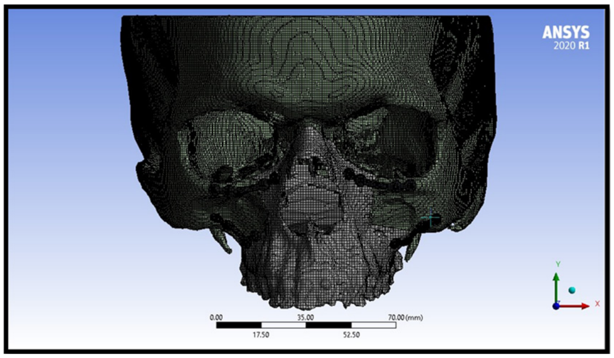


Figure 5: Depict the meshed model of non-comminuted Le Fort II fracture with miniplate osteosynthesis- frontal view

Inclusion Criteria

CT scan of an adult male with a non-fractured midfacial skull

Exclusion Criteria

- CT scan of participant with gross facial asymmetry.
- CT scan of participant with space-occupying lesion invading mid facial region.
- CT scan of participant with healing, malunited or non-united fractures of mid-facial region.

Results

Group A (Le Fort I, II, and III fractures without miniplate osteosynthesis) von Mises stress values were not simulated. This was because, despite the boundary conditions, the fracture fragments were not secured, and thus the surface contact between them was bonded. As a result, the obtained values were insignificant. The yield strength of metals can be defined as the amount of force required to deform the material. Ti-6Al-4V (TAV) (grade 5) is the titanium alloy used universally in maxillofacial osteosynthesis. Its yield strength is 880 MPa (Riviş M, 2020).

Collating the von Mises stress values on the bone in Le Fort 1 fracture and the normal models, a significant difference was noted in the closing phase on the left side. In the closing phase, the highest stress value was over the left pyriform rim region of 66.09 MPa, compared to 0.496 MPa in the normal closing phase. The Von Mises stress recorded on the miniplate and screw fixation was the highest on the left zygomatic buttress region in the closed jaw reported to be 499.8 MPa which is for the posteriorly placed L plate. In the Le Fort II model, the stress values over the right zygomatic buttress and the right infraorbital rim region were in the identical range of 55 to 70 MPa. Analyzing the stress values over the bone in the normal model and the Group B model of Le Fort II fracture, a remarkable escalation was noted in the open and closed jaw movement (Table 4). Considerable stress was generated on the miniplate over the left zygomatic buttress (1236.7 MPa) and right infraorbital rim (1416.1 MPa) in the close jaw, indicating a concentrated stress pattern in the time-dependent close jaw motion. In the Le Fort III model, the fronto-nasal region showed a significant increase of stress in the open and closed jaw, with the greatest stress observed in the close jaw of 23.72 MPa compared to the stress obtained in the normal model of close jaw (3.8 MPa). A noteworthy finding was the similarity in the stress concentration in the open jaw movement, wherein the normal model the stress observed was 0.006 MPa on the left and right sides, respectively and the open jaw with fracture indicated values of 0.06 and 0.07 MPa on the left and right sides, respectively. The stress obtained in the close jaw showed an increase of 141.39 and 198.11 MPa (Figure 6). The stress over the bilateral infraorbital rims depicted an increasing trend. The significant stress observed was in the close jaw motion of about 7.9 MPa compared to the normal stress in the region, which was about 1.8 MPa bilaterally. The stress recorded over the hardware was also on the higher side due to the increased loading conditions in the closed jaw motion. The maximal stress was over the miniplate osteosynthesis at the frontonasal region of 755.53 MPa, followed by the left zygomatic arch (633.08 MPa) and the left fronto-zygomatic region (557.8 MPa) in the closing jaw (Table 5). On comparison with the stress recorded in the Le Fort II and III fractures, an indistinguishable trend ranging from 0.020 to 0.055 MPa was observed at the bilateral infraorbital rims in the open jaw movement. A decline in the stress concentration was noted at the bilateral infraorbital rims in the closing movement of the jaw from 66.89 MPa in the Le Fort II model to 7.923 MPa in the Le Fort III model (Figure 7). The left pyriform rim recorded the peak stress concentration of 462.02 MPa in the close jaw motion, whereas a peculiar stress value of 23.954 at the right pyriform rim in the close

Table 4: showing Von Mises stress on the bone in the non-comminuted Le Fort I, II and III fractures in the opening movement of jaw.

Anatomic region	*Open jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	0.04	0.0051
Pyriform rim	0.057	0.01
Anatomic region	*Open jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	0.013	0.021
Pyriform rim	0.003	0.0064
Infraorbital rim	0.038	0.023
Anatomic region	*Open jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	0.075	0.0.051
Pyriform rim	0.023	0.035
Infraorbital rim	0.055	0.034
Frontozygomatic suture	0.067	0.074
Frontonasal suture	0.018	
Zygomatic arch	0.327	0.402

Table 5: shows Von Mises stress on bone in the non-comminuted Le Fort I, II and III fractures in the closing movement of jaw

Anatomic region	*Close jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	31.56	26.51
Pyriform rim	66.09	19.637
Anatomic region	*Close jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	36.041	58.336
Pyriform rim	24.23	44.74
Infraorbital rim	45.536	66.89
Anatomic region	*Close jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	5.894	18.708
Pyriform rim	3.046	3.918
Infraorbital rim	7.816	7.923
Frontozygomatic suture	141.31	198.11
Frontonasal suture	23.722	
Zygomatic arch	81.33	151.87

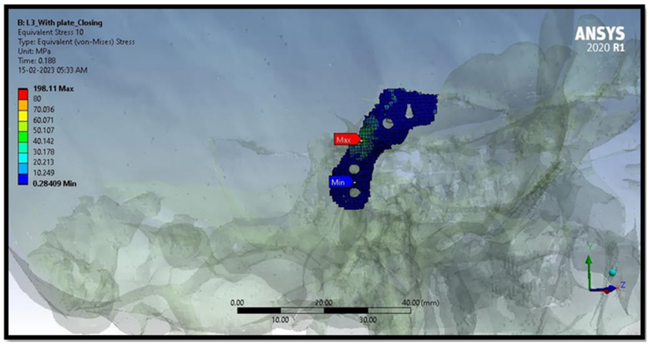


Figure 6: Depict the von Mises stress (198.11 MPa) on the right fronto-zygomatic suture region in the close jaw in the non-comminuted Le Fort III fracture with miniplate osteosynthesis.

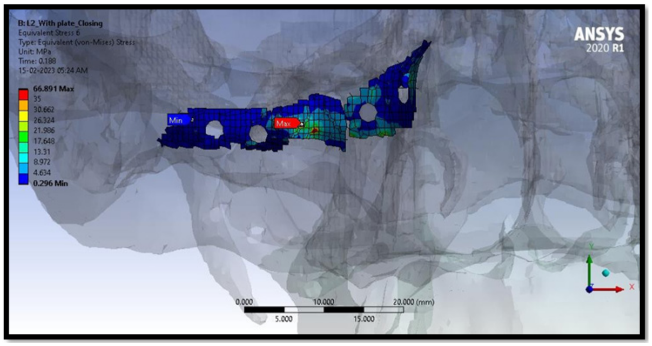


Figure 7: Depicts the Von Mises stress (66.89MPa) on the right infraorbital region in the close jaw in the non-comminuted Le Fort II fracture with miniplate osteosynthesis.

jaw motion was recorded. As a result of the comminution, the maximal stress recorded over the zygomatic buttress was higher (197.89 and 226.54 MPa) compared to the non-comminuted (31.56 and 26.517 MPa) Le Fort I model in the close jaw movement. The stress concentration pattern in the open jaw movement was similar to the non- comminuted model, ranging from 0.01 to 0.05 MPa in the bilateral zygomatic buttress and pyriform rims. The highest Von Mises stress observed on the miniplate osteosynthesis in the comminuted Le Fort I model was 2643 MPa on the left posteriorly placed L-shaped plate over the zygomatic buttress in contrast to 519 MPa recorded over the miniplate fixation of the right zygomatic buttress. This is of importance because it clearly exceeds the yield strength of the titanium alloy used in miniplate osteosynthesis (880 MPa). A notable difference in the stress values over the bilateral zygomatic buttresses and infraorbital rims was not established, collating with the non-comminuted Le Fort II model in the open jaw movement. However, the stress recorded in the close movement of the jaw escalated to 895.67 MPa over the comminuted left infraorbital rim as opposed to 45.537 MPa over the left infraorbital rim in the non-comminuted Le Fort II model. The greatest value illustrated over the hardware was 19,904 MPa on the right infraorbital rim in the close jaw compared to the value of 1416 MPa on the right infraorbital rim in the close jaw of the non-comminuted Le Fort II model. The highest value obtained over the hardware exceeds the yield strength of titanium alloy (880 MPa) by a huge difference. The zygomatic buttress miniplate fixation also recorded a peak stress concentration of 2925 MPa in the comminuted Le Fort II model contrary to the stress value recorded of 1236.7 MPa in the non-comminuted Le Fort II model in the close jaw movement of the jaw. A similar stress range of 0.18 to 0.25 MPa was recorded over the bone at the points of fixation described above in the open jaw movement. A remarkable stress value recorded was over the comminuted frontonasal region (16.8 MPa), in contrast to 0.18 MPa in the non-comminuted frontonasal region in the open jaw movement. Compared with the non-comminuted Le Fort III model, the stress values recorded decreased in the comminuted Le Fort III model at the bilateral frontozygomatic suture region. The maximum stress was recorded on the frontonasal region in the close jaw movement of jaw in the comminuted Le Fort III model, measuring 812.11 MPa (Figure 8). A significant difference in von Mises stress was noted in comparison with comminuted and non-comminuted Le Fort III models in the open jaw movement, with the highest recording over the frontonasal region (727.49 MPa) in the comminuted model (Table 6).

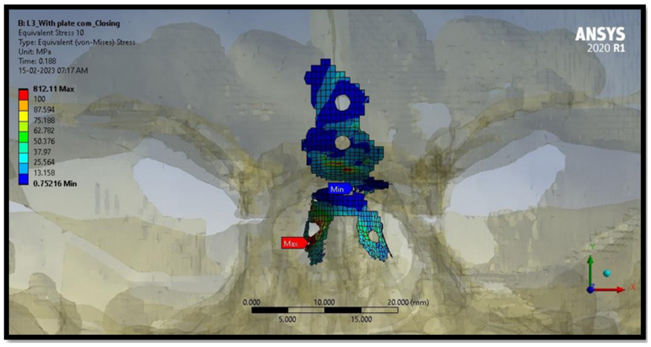


Figure 8: Depicts the von Mises stress (812.11 MPa) on the frontonasal region in the close jaw in comminuted Le Fort III fracture with miniplate osteosynthesis.

Discussion

Midfacial bones need considerable force to get fractured and are commonly caused by interpersonal violence and motor vehicle accidents. Blunt injuries to the midface frequently involve the malar region (Walker, 2013). Because of the anatomy of the maxilla and the nearby structures, energy is dissipated by breaking the underlying bone to lessen the inertial load, protecting the globe and the brain and so the midface was referred to as the 'crumple zone of the face' (Banks P,1987). A retrospective clinical study of two decades assessed the surgical treatment of Le Fort fractures in Bang Pong Hospital, Thailand and found most of the patients were male (84.4%) and were affected in the third decade of life (54.7%) with an age range of 13 to 65 years old (Jarupoonphol V, 2001). Manson *et al.*, 1986 measured a Le Fort I: II: III ratio of 30:42:28. The midface fractures are an amalgamation of varied other fractures, including the zygomatic complex, the maxilla, the orbit, the nasoethmoidal region, and concomitantly the frontal bone as well. The perplexing three-dimensional anatomy of the zygomaticomaxillary complex may make adequate reduction challenging, especially when

Table 6: showing Von Mises stress on bone in the comminuted Le Fort I, II and III fractures in the opening movement of jaw

Anatomic region	*Open jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	0.028	0.0162
Pyriform rim	0.3	0.002
Anatomic region	*Open jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	0.0085	0.0086
Pyriform rim	0.0037	0.00064
Infraorbital rim	0.029	0.0182
Anatomic region	*Open jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	0.04	0.012
Pyriform rim	0.075	0.065
Infraorbital rim	0.037	0.0337
Frontozygomatic suture	0.1997	0.175
Frontonasal suture	16.8	
Zygomatic arch	0.25	0.186

Table 7: showing Von Mises stress on bone in the comminuted Le Fort I, II and III fractures in the closing movement of jaw

Anatomic region	*Close jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	197.89	226.54
Pyriform rim	462.02	23.954

Anatomic region	*Close jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	33.67	42.58
Pyriform rim	149.9	100.3
Infraorbital rim	895.67	520.18

Anatomic region	*Close jaw (MPa)*	
	Left	*Right*
Zygomatic buttress	4.22	4.16
Pyriform rim	24.06	26.52
Infraorbital rim	13.52	3.14
Frontozygomatic suture	29.13	122.87
Frontonasal suture	812.11	
Zygomatic arch	23.03	70.56

there is severe displacement or comminution in view of the fact that it has the ability of rotational displacement in axial, coronal and sagittal planes. Also, the zygomaticomaxillary complex cannot be said to be acting as a simple structural unit because of the pattern of the tensile and compressive stress trajectories, which suggest that compound moment arms are loading it under bite force conditions (Pakdel AR,2017) Table 7.

Bone buttressing steers the evaluation of the strength of the plate fixation systems. Armstrong *et al* in 2001 gave a probable explanation for bone buttressing that it is the strength contributed to the system through the resistance to gap formation contributed by compression of the bone across the border on the same side the force is being applied. The prime goal in the management of Le Fort fractures follows a sequential protocol of securing the airway and controlling the bleeding. In patients with diagnosed midface fractures; cervical spine, neurologic, chest, and abdominal injuries are thoroughly ruled out. The next important step to address is the restoration of pre-morbid dental occlusion and facial aesthetics. Achieving a satisfactory occlusion depends on the number of fixation plates used on the key buttress regions and the stability of the plates. Nerve paresthesia, infection, CSF rhinorrhea, malocclusion, septal deviation, poor aesthetic outcomes, and nonunion or malunion are all potential complications of maxillary fractures. Amongst these, a recurring outcome after the surgical fixation is the anterior open bite and posterior gagging (8–10%) in the occlusion which is overlooked (Buehler JA,2003). Attributed to the supposition is the downward and backward slope of the anterior cranial base and the masticatory muscle activity (Stanley,1985) Hence the rationale of the present study was to investigate this supposition.

There are two methods of performing experimental *in-vitro* research in cases of facial trauma: Cadaver studies and virtual simulations utilizing finite element analysis (FEA). Due to the lack of sufficient cadaver specimens and the required tools, cadaver studies can only address a particular question.3D-FEA is a numerical method for addressing biomechanical questions and is a powerful research tool that can provide precise insight into the complex mechanical behavior of the maxilla affected by mechanical loading, which is otherwise difficult to assess (Soares CJ, 2018). According to Atac *et al.*, 3D-FEA allowed for a more realistic representation of the stress distribution in the fixative material and the adjacent bone tissue than would be the case with a 2D simulation. If a suitable model is provided, it is also possible to estimate a specific impact force according to an existing fracture pattern (Schaller A, 2012). Its wider implementation in research and practice should be prioritized in order to reduce the risk of unnecessary failure, expand knowledge of oral and maxillofacial biomechanics, introduce enhanced osteosynthesis solutions, reconstruction scaffolds, biomaterials, or implant components, and select the most optimal treatment materials and approaches (Soares CJ, 2018). As a result, the current finite element study with a simulation of masticatory muscles provided insight into the stress occurring in the comminuted and non-comminuted Le Fort fracture patterns with conventional miniplate osteosynthesis. These patterns are compared to clinical case findings. This study's FEA models made several assumptions about the simulated structures. The models' structures were all assumed to be homogeneous, isotropic, and linearly elastic, and the structures modeled were the muscle forces upon the midface, which were dynamic in nature. Yamaguchi *et al.* in 2011 noted that in regard to the simulation of the muscular activity during the masticatory cycle, the human masticatory system has a very complex performance that necessitates the coordinated and balanced activities of the left and right masticatory muscles.

Electromyography (EMG) recordings present a challenging method for investigating masticatory muscles, which contributes to our limited understanding of their function. The electromyograph may be misplaced depending on where the muscle is located. Given the observations of various researchers, Sessle and Gurza**,** Murray *et al*., signified that the location of the jaw is a significant determinant of its EMG activity, which is crucial in human lateral pterygoid muscle. The history of the management of facial fractures by internal fixation dates back to 1881 when Gilmer secured the fragments using two heavy rods on either side of the fracture. Deveci *et al.,* in 2004 studied the biomechanical analysis of rigid fixation in the midface fractures and inferred their observations in the experimental study that the frontozygomatic suture was the most crucial location in fixation because deformation and failure of the plates were consistently seen there. High-energy face injuries cause the facial skeleton's buttress support to be disrupted, and they are repaired with rigid metal plates and screws (Francel TJ,1992). Sansgiri *et al.,* in 2020 compared the treatment outcomes following the fixation of midface fractures with microplates to that of mini plates and concluded that microplate osteosynthesis gives equivalent results in terms of stability and function and clinical superiority in terms of aesthetics. In most maxillofacial osteotomies and fractures, titanium plates and screws aid in internal fixation. Tensile strength and hardness are two crucial qualities such a material must have to perform its functions. With their excellent resistance, elasticity, tensile strength, and biocompatibility, titanium alloys have swiftly emerged as the best choice for producing a good contour of the replacement bone structure. With the apposition of bone tissue in the reconstruction area, titanium's composition significant biocompatible property controls the activation of the osteointegration process (Kasemer M, 2016). For the above-mentioned reasons, titanium miniplate osteosynthesis is considered in the present study to be evaluated for its stability in comminuted and non-comminuted midface fractures under dynamic masticatory loading conditions.

The conventional titanium mini plates were well-adapted to the adjacent bone used in the current study because the gap created between the two fractured segments reduced bone contact, and the bent plate provided adequate rigidity for the fixation of the segments. Only a few studies represent the biological modeling of the midface for assessing osseous strain patterns and plating systems. Physical models were difficult to create. Chewing forces were challenging to quantify because they depend on the state of the dentition, the food being consumed, the pattern of chewing, the length of time the food is being masticated, and the measurement technique, which are multidirectional. In 2008, Atac *et al*. concluded that the oblique and horizontal chewing forces cause more stress formation than vertical ones.

In order to stabilize this typical fracture pattern, minimal fixation along the axis of the compressive principal stress at the zygomaticomaxillary buttress and stability along the axis of the tensile principal stress at the lateral orbital rim were necessary. The latter had the implication that in non-comminuted fractures at the zygomaticomaxillary site where the bone is adequately buttressed, low-profile plates and minimal fixation may be sufficient to withstand shear displacement.

The clinical observation of anterior open bite malocclusion in Le Fort pattern maxillary fractures coincided with the pattern of tensile stresses posterior to the maxilla. While the rest of the maxilla is in vertical compression, the posterior maxilla was subjected to tensile forces, which caused posterior elongation and premature posterior contact (Pakdel AR, 2017). The arrangement of these patterns suggested that the lateral maxillary buttress is the primary compressive load-bearing structure of the midfacial craniomaxillofacial skeleton under masticatory load, whereas the other assumed buttresses either have a minimal or nonexistent role in reducing vertical compressive masticatory forces. The Von Mises stress on the miniplate osteosynthesis at the inferior orbital rim in comminuted and non-comminuted Le Fort II models in the opening phase of jaw were insignificant, while there was maximal Von Mises stress at the lateral orbital rim and nasofrontal region and maximal compression at the lateral zygomaticomaxillary buttress. However, it was observed that the inferior orbital rim is under remarkable stress in the comminuted and non- comminuted Le Fort II fractures with miniplate osteosynthesis in the closing phase of mastication. As previously deduced from experiential evidence, the justification for exposure extension should be driven primarily by the requirement to increase reduction accuracy rather than maximize fixation. The observations in this study indicate that between the comminuted and non- comminuted Le Fort fractures, the latter underwent increased stress distribution implying usage of thicker profile plates in the areas of multiple bone fragmentation. Increased clinical studies correlating the FEA findings may help achieve decreased biomechanical stress on the fractured midfacial skeleton by a new osteosynthesis solution.

Therefore, this study directed the maxillofacial surgeons and researchers to discover a design and a material which is sturdy enough to withstand the masticatory muscle forces in comminuted and non-comminuted midface fractures. The stability of the bone fragments after conventional miniplate osteosynthesis was remarkably affected in the comminuted and non-comminuted Le Fort I, II and III fractures leading to the clinical outcomes faced by the maxillofacial surgeon post-operatively after open reduction and internal fixation.

A FEM study conducted in 2014 by Janovic *et al* revealed a pattern of occlusal load distribution that was only partially consistent with the traditional idea of buttresses. The cortical bone clearly showed areas of the nasomaxillary and zygomaticomaxillary buttresses, with the former showing more stress. The relative contribution of cortical and trabecular bone to the masticatory load transmission at the zygomaticomaxillary buttress is a topic of debate (Schaller A, 2012). The present study's findings are consistent with the conventional theory that the pterygomaxillary buttress is the path taken by masticatory load transfer in the posterior maxilla through the medial pterygoid muscle. Hence, the Von Mises stresses obtained in this study FEA are greater in the closing phase of the masticatory cycle. This area had been sporadically studied in earlier strain gauge and FE research.

The lateral orbital rim appears to be constrained rigidly by the sutural articulation at the frontal bone. This illustrates how a skeletal structure's function may conflict with the pragmatic conclusions drawn from its external shape. This area of the zygoma resembles a pillar, which indicates that it is designed to support compressive, vertically oriented stresses during masticatory load (Pakdel AR, 2017). However, the FEA model showed that this region was beam bending even when loaded with the maximum masticatory force. Analyzing the stress recorded over the zygomatic buttress in the Le Fort I, II, and III fractures, the peak stress of 58.336 MPa was concentrated on the right zygomatic buttress of the non-comminuted Le Fort II fracture in the close jaw.

Owing to the increased loading conditions in the closed jaw motion, the highest stress obtained in the non-comminuted Le Fort III model was over the miniplate osteosynthesis at the frontonasal region (755.53 MPa), followed by the zygomatic arch and the fronto-zygomatic region. The probable explanation can be the fragile bone architecture in the nasofrontal region. The deformation in the plate is the greatest, hinting towards the need to develop more stable hardware to withstand these high loads. The hardware is close to a thin skin surface because there is a lack of soft tissue coverage around the orbits, naso-orbital ethmoid region, and frontal bone. Miniplates and now microplates reduce the rate of removal in areas where hardware retention is not required to counter muscle contractions (i.e., forces of mastication), particularly in the supraorbital, frontal, and naso-orbital ethmoid locations (Francel TJ, 1992). An appreciable difference in the Von Mises's stress developed on the right and left sides of the respective regions studied is in all likelihood due to the anatomical variations in the morphology of the buttresses and the usage of the dominant side while chewing. A study designed with a greater sample size may exclude the bias encountered.

In the comminuted models as well, the important finding to note was the Von Mises's stress over the traditional miniplate osteosynthesis exceeding the yield strength of the titanium alloy. This represents that the miniplates, especially on the zygomatic buttresses are under constant stress leading to microstructural deformation in the plates and screws. This can also be attributed to the comminution of the underlying bone, which fails to provide adequate support to the hardware, thereby generating a concentrated stress pattern explaining the clinical consequences post-operatively. An increment of greater than 200 MPa was found on the hardware upon collating the comminuted and non-comminuted Le Fort III models in the close movement of the jaw. The peak deformation of the miniplate on the frontonasal region is of clinical concern because it exceeds the yield strength of titanium alloy 3 times its value.

Conclusion

The study aimed to build a digital model of midface based on a real image examination of a patient with a history of trauma and performed a dynamic FE analysis of the midface trauma mechanics. The masticatory muscle dynamics were well simulated as a result of the finite element method and their significant role was proven in the biomechanics of midface trauma. Anatomical variations and orientation of the patient during computerized tomography (CT) scan may account for the study bias. To summarize, this study introduces reliable biomechanical skull models that are more detailed and enable the attribution of various material properties to anatomical components. The simulated virtual models are helpful in evaluating the stress distribution on the comminuted and non-comminuted bone in Le Fort fracture patterns.

In conclusion, the biomechanical stability of conventional miniplate osteosynthesis is insufficient to secure the midface fractured bone under a masticatory load. Though the findings and observations in the present study support the post-operative clinical consequences faced by the maxillofacial surgeon, a larger sample size with clinical correlation would definitely provide a better understanding of the biomechanics in comminuted and non-comminuted midface trauma.

Acknowledgement

Nil

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