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Finite Element Simulation of Displaced ZMC Fracture After Fixation with Resorbable and Non-Resorbable One-Point Mini-Plates and Applying Normal to Severe Occlusal Loads

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Abstract

Background: ZMC fractures are the second most common trauma of the face. Therefore, their treatment (including methods of fixation) is of clinical significance.

Objectives: Due to the lack of studies on many resorbable and non-resorbable fixations of the zygoma, this finite element analysis assessed for the first time displacements and dynamics of the zygoma fixed using three 1-point resorbable and three non-resorbable plates under normal and severe mastication forces.

Methods: After creating the 3D model of the zygoma and its adjacent bones based on a CT scan of a male patient, with linear fractures but without severe dislocations, three one-point resorbable and three similar one-point non-resorbable mini-plates were used to fix the zygoma with miniscrews. The zygomaticomaxillary buttress (ZMB), infraorbital rim, and frontozygomatic (FZ) suture were stabilized using L-shaped four-hole, curved five-hole, four-hole miniplates, respectively. The simulated zygoma was subjected to 150N and 750N loads. Minimum and maximum of stresses, strains, displacements, and rotational displacements of the zygoma were measured.

Results: All four parameters were much smaller in non-resorbable fixations compared to resorbable ones. In severe maxillary force, the parameters stress, strain, and displacement increase considerably. Among these, FZ might cause smaller displacements. Resorbable plates might not be optimum choices for one-point fixation of cases with the heavy mastication loads.

Keywords: Fracture, Zygomaticomaxillary Complex, Internal Fixation, Displacement, Finite Element Analysis (FEA)

1. Background

The zygomaticomaxillary complex (ZMC) is a prominent structure in the midface and is crucial for the structure, function, and even esthetic appearance (1, 2). ZMC fractures (malar, trimalar, tripod, tetrapod, or quadripod fractures) are very common and can occur at the zygomaticotemporal suture, the frontozygomatic (FZ) suture, the zygomaticomaxillary buttress (ZMB), and the zygomaticomaxillary suture (3-7). Its fracture can cause several complications, such as esthetic problems, mandibular restriction, occlusion gagging, injury to the infraorbital nerve, sensory disturbances, subconjunctival ecchymosis, enophthalmos, diplopia, or flattening of the cheek (1, 8-12).

ZMC fractures are usually difficult to manage (2, 12). The goals of the surgical management include precise reduction of the displaces structures, and if needed, constraining and fixation of the displaced segment to reduce the complications and improve healing (1, 13, 14). Various techniques have been introduced and tested for this purpose, such as wire fixation, which was not quite satisfactory and the internal fixation using mini-plates , which are accepted broadly today (4, 15-24). Nevertheless, the literature on the position of stabilizers is controversial (1).

2. Objectives

Finite element analysis (FEA) is a method to simulate the dynamics of physical objects and is used frequently in dentistry; with this method, it is possible to examine the three dimensional distributions of stress, strain and displacement and stability in a variety of the different methods of fixation of the zygomatic bone (25-29). However, no FEA studies have assessed the stability of ZMC fractures fixed using internal fixations. Therefore, this preliminary study was conducted.

3. Methods

The CT scan of a patient with a zygomatic bone fracture was taken for only treatment purposes retrospectively, that included after evaluating an archive of CT scans at a private radiology center. The protocols were approved by the research committee of the university. The inclusion criteria were: being male, about 30 - 40 years old, having linear fractures without severe displacements. The exclusion criteria were occlusal, craniofacial, or pathological problems before the injury, or missing bone fragments.

The modeling and computer simulations were performed by two facial surgeons and a biomechanical engineer in Toronto, Canada. Each slice of the CT Scan with 205 sections and slice thickness of 0.5 mm were converted to DICOM format and fed to the Mimics Innovation Suite V. 17.0.0.435 X64 Platform (Materialise, Leuven, Belgium) in loss-less compression mode for separation and measurement. The information was accessible in the software environment in three windows representing the three main sagittal, coronal and axial sections.

To increase the accuracy of the model, it was constructed in all three spatial planes of axial, coronal, and sagittal by manual segregation with a slice thicknesses of 0.5 mm. The complete model of zygoma in which the cortical and cancellous bones were separated ultimately transferred from Mimics to 3-Matic Research 9.0.0.231 (Materialise bv, Leuven, Belgium) for simulating solid 3D geometrical surfaces.

Fixation plates (Inion CPS Fixation Systems, Tampere, Finland) were reverse-engineered, and the plates were fixed on the model. All mini-plates used were 2 mm thick. To fix the zygomaticomaxillary buttress area, an L-shaped four-hole plate was used. The infraorbital rim area was fixed with a curved 5-hole mini-plate, and the frontozygomatic suture area with a 4-hole mini-plate, respectively. Then all mini-plates were fixed with 6mm mini-screws (Jeil Medical Corporation, Korea, Figure 1).

In the next step, the constructed models were fed to the Finite Element Abaqus program (Dassault Systems, SolidWorks Crop, 2013) for mechanical analysis to determine the stress, strain, displacement, and rotational displacement of each model under normal and maximal forces of mastication. The FEA breaks down the whole engineering model into smaller components called elements. Each element has nodes with input values (loading, bearing, boundary conditions) and output (results) assigned to them. In this study triangular volumetric elements were used for modeling. We used the maximum possible number of elements to improve the accuracy (241286 elements with 483042 nodes).

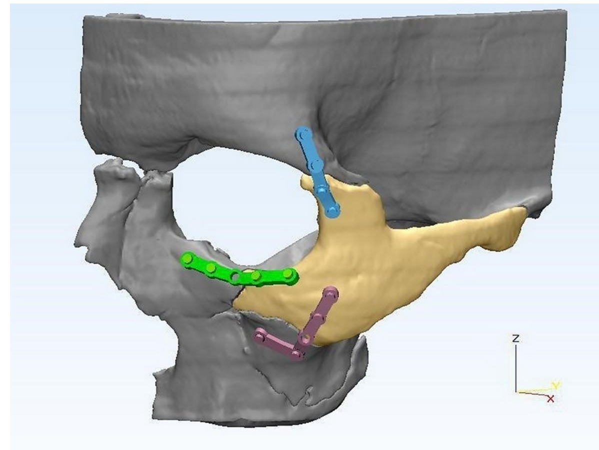

Figure 1. The simulated model in Mimics

The physical properties of the modeled objects were entered to the software using the preprocessor option in the material models section and then by selecting the elastic and then the isotropic options. These comprised the Poisson coefficient for the bone (0.3), non-resorbable screw and plaque (0.33), resorbable screw and plaque (0.46), as well as the modulus of elasticity for the bone (14.8 GigaPascals [GPa]), non-resorbable plate and plaque (105 GPa), and resorbable plate and plaque (3.15 GPa).

In the next step, meshing was done automatically by the Free Mesh command. This was done independently for bones, screws, and plates. Afterwards, the location of force exertion was set at the center of gravity of the zygoma. The force was set at 150 and 750 N along the Z axis (perpendicular to the occlusal plane). The force magnitudes were determined based on the study of Okiyama et al. (30). At the end, the outputs regarding the stress, strain, displacement, and rotational displacement were obtained after loading.

4. Results

4.1. Stress

Non-resorbable types tolerated smaller stresses than their resorbable counterparts. Under 150N load, the highest stresses in the resorbable and non-resorbable groups belonged to Rim and ZMB, respectively (Table 1).

4.2. Strain

Apart from FZ fixation under the 150N load in which the non-resorbable type had a much higher strain than its resorbable counterpart, non-resorbable fixations showed much smaller strains than their counterpart resorbable ones. Under the 150N force, the maximum strain of non-resorbable fixations were observed in the case of FZ fixation; however, in the case of resorbable categories, the

Table 1. Maximum and Minimum of the Parameters

Type/Force	Method	Strain, Unit-Less		Stress, N/mm^2		Dis, mm		Rot Dis, mm	
		Max	Min	Max	Min	Max	Min	Max	Min
NR									
150 N	FZ	0.7793	-0.00144	500	0	0.3972	0	0.3217	0
	Rim	0.01664	-0.01348	640.3	0	1.965	0	0.04944	0
	ZMB	0.008158	-0.00133	850.4	0	0.535	0	0.02942	0
750 N	FZ	0.04208	-0.00776	2700	0	2.145	0	0.1737	0
	Rim	0.08988	-0.07277	3458	0	10.61	0	0.267	0
	ZMB	0.04405	-0.0072	4592	0	2.889	0	0.1579	0
R									
150 N	FZ	0.1583	-0.00955	1434	0	2.274	0	0.05288	0
	Rim	0.205	-0.07359	2824	0	22.86	0	0.3821	0
	ZMB	0.1729	-0.01242	1142	0	9.453	0	0.1911	0
750 N	FZ	0.8546	-0.05157	7746	0	12.28	0	0.2856	0
	Rim	1.107	-0.399	15250	0	122.5	0	2.063	0
	ZMB	0.9678	-0.06707	6164	0	51.04	0	1.032	0

Abbreviations: Dis, displacement; FZ, frontozygomatic; Max, maximum; Min, minimum; NR, non-resorbable; R, resorbable; Rot Dis, rotational displacement; ZMB, zygomaticomaxillary buttress.

Rim, ZMB, and FZ had a high strain. Under the 750N force, the maximum rotational displacements of both groups were observed in the Rim, ZMB, and FZ groups (Table 1). Under the 150N force, all non-resorbable categories except FZ showed minimal strains (Table 1). Under the 750N force, non-resorbable categories had low strains, while resorbable methods had much higher strains (Table 1).

4.3. Displacement

Resorbable fixations showed greater displacements than non-resorbable ones. Under the 150-N force, the rim fixation showed the highest displacements in both resorbable and non-resorbable plates followed by ZMB. Again, these fixations had the most great displacements under 750 N (Figures 2 - 4 and Table 1). When the 150 N force was applied, all non-resorbable categories except for the rim fixation showed minimal displacements. Under the 750N force, no cases showed a minimal displacement either resorbable or non-resorbable.

4.4. Rotational Displacement

Except in the case of FZ fixation under the 150-N load, non-resorbable fixations showed smaller rotational displacements than their counterpart resorbable ones. Under the 150N force, the maximum rotational displacements of resorbable fixations were seen in the case of fixation of the rim followed by ZMB while among the non-resorbable models, the FZ had a much higher rotational displacement followed by rim and ZMB. Under the 750-N force, the maximum rotational displacements of both groups were observed in the rim and ZMB fixations (Table 1). Under the 750-N force, none of cases had minimal rotational displacements.

5. Discussion

In this study, the 150 N and 750 N loads were exerted to the system, as the normal and maximum loads of occlusion on molar teeth (30). The best fixation is the method that has the least amount of displacement and rotational displacement, which ensures sufficient initial stability. Internal fixation includes resorbable and non-resorbable systems, one of which is the fixation by a mini-plate. This method is a system of plates attached to the bone via the bone-screw joint (20, 21). Therefore, the biomechanical function of fixation systems depends clinically on the interaction of all three components, i.e., plate, screw, and the bone. The conformation of the plate surface with the bone has a significant effect on the efficacy of screw in attaching the bone to plate (31).

According to the results of this study, FZ region fixation is the best fixation for performing one-point fixation at 150 and 750 N. However, Sridhar et al. (32). compared the fixation of FZ and ZMB, and concluded that there was no difference in terms of function and stability between the two methods, which this contradicted our findings. Still, ZMB may be a better option due to its easier access, better reduction and sight, and lower scarification (33). Wittwer et

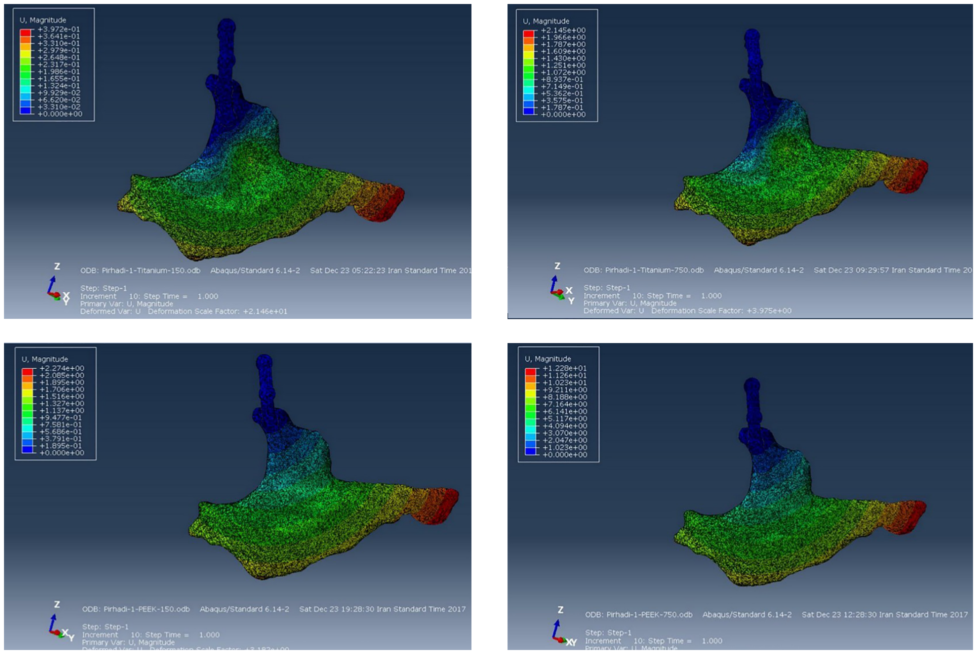

Figure 2. Displacement analysis of FZ non-resorbable (top row) and resorbable (bottom row) models under the 150 N force (left column) and 750 N force (right column)

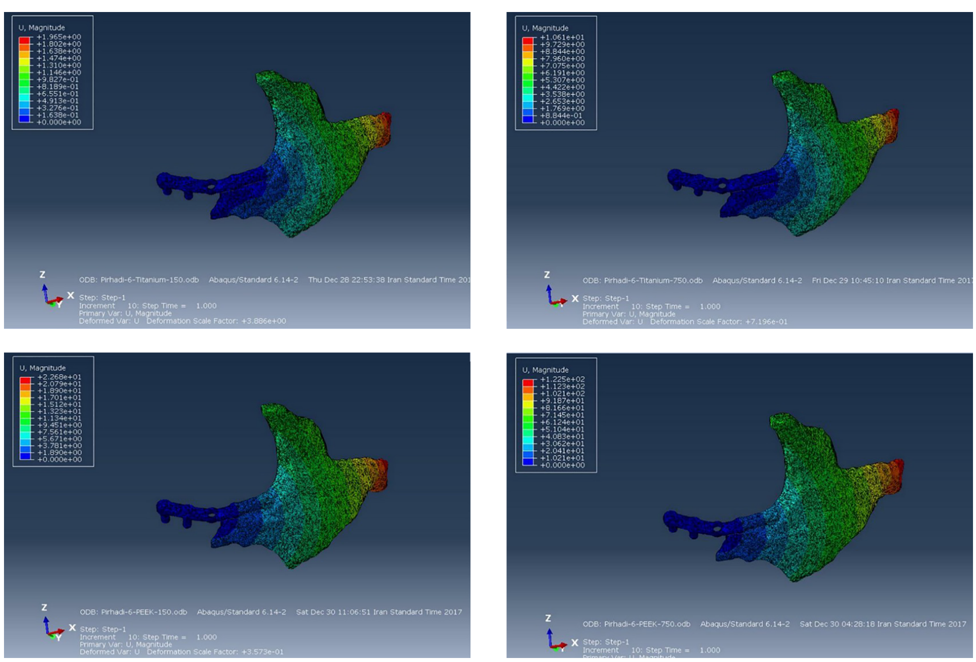

Figure 3. Displacement analysis of Rim non-resorbable (top row) and resorbable (bottom row) models under the 150 N force (left column) and 750 N force (right column)

al. (34) concluded that FZ would be the best one-point fixation method for resorbable fixation plates. Also, Mitchell et al. (35) and Champy et al. (36) all confirmed FZ fixation for sufficient 3D stability, which is consistent with the results of the present research.

The reason for assessing the resorbable internal fix-

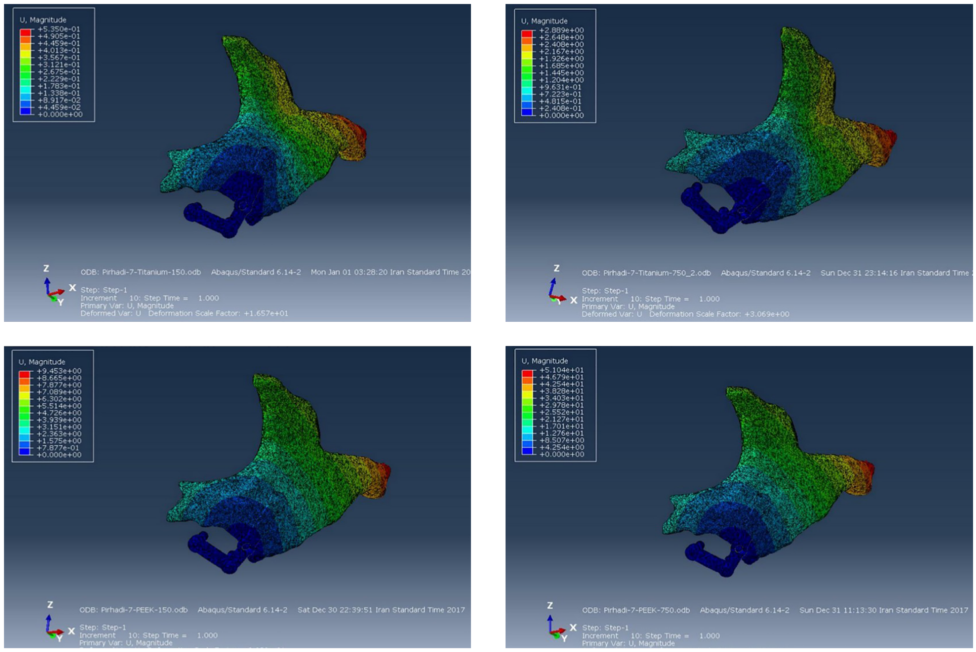

Figure 4. Displacement analysis of ZMB non-resorbable (top row) and resorbable (bottom row) models under the 150 N force (left column) and 750 N force (right column)

ation method in this study was the presence of clinical evidences indicating its appropriate stability (37, 38), as well as lack of any studies on their biomechanical behavior. Furthermore, unique physical and chemical properties of such resorbable fixation plates (27) and their fewer complications compared to the non-resorbable ones (39) can make this system as a suitable substitute for non-resorbable types in internal fixation (40-43). Use of metal plates may accompany complications such as, pain and post-corrosion inflammation, loosening of screws, being palpable beneath the skin, temperature sensitivity, the need for a secondary surgery to remove them, interference in radiographic images due to superimposition on bony structures, and limiting the growth of children's bones (44-47). In a study on mechanical properties of resorbable systems, Claes (27) found that resorbable devices have an elastic-viscous behavior and their flexibility is about 10 times higher than non-resorbable systems (27). Since the modulus of elasticity of resorbable polymers is less than the non-resorbable types and since their modulus of elasticity is closer to the bone, the movement of the fixed piece might be more noticeable in vitro in the case of resorbable cases than non-resorbable ones (48, 49). Absorbable fixation systems might have complications, including foreign body reactions and mobility; however, their complications might not be significant in bimaxillary operation, bilateral sagittal split osteotomy, and Le Fort I operation (50).

5.1. Conclusions

The findings of this simulation suggest that under normal loads, the stability would be higher compared to maximum loads. Non-resorbable one-point fixations have much better stabilities in all situations than resorbable ones. Single-point fixation in the rim area is unstable, and thus is not a proper method of fixation. Results of this preliminary study should be followed by the future clinical studies.

Footnotes

Authors' Contribution: Farzin Sarkarat and Roozbeh Kahali mentored the theses. Sogand Ebrahimi and Maryam Khosravi performed experiments and wrote theses. Amirparham Pirhadi Rad performed computer simulations. Vahid Rakhshan wrote the article.

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Ethical Considerations: Not applicable. There was no humans or animals.

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