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Original Article

Stability and Dynamics of Zygomaticomaxillary Complex Fracture Treated Using Non-resorbable and Resorbable 2- and 3-Point Miniplates, Under Physiological and Maximal Occlusal Loads: A Finite Element Analysis

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Abstract

Background: Given that zygoma fractures are the second most common facial trauma, knowledge of their treatments is of clinical value. Among these are fixation methods, which despite their importance are neglected in many aspects.

Objectives: Therefore, for the first time in the literature, the present finite element analysis evaluated displacements and dynamics of the zygoma fixed using four 2- and 3-point resorbable and four non-resorbable plates under normal and maximal mastication loads.

Methods: A maxillofacial CT scan of a man with linear fractures without severe displacements was used to model the zygoma and its adjacent bones. Seven combinations of resorbable and seven combinations of non-resorbable mini-plates 2mm thick were fixed on the zygoma (orbital rim, zygomaticomaxillary buttress [ZMB], and frontozygomatic [FZ]) using 6mm miniscrews. ZMB was fixed using an L-shaped 4-hole plate. The infraorbital rim was fixed with a curved 5-hole miniplate. The FZ suture area was fixed with a 4-hole miniplate. The model underwent 150N and 750N loads. Minimum and maximum displacements, rotational displacements, stresses, and strains of the zygoma models were calculated.

Results: Non-resorbable fixation methods can yield much smaller stresses, strains, and displacements compared to resorbable fixations. Also the parameters were much smaller under the 150N load compared to the 750N load. The worst results belonged to the fixation of Rim and ZMB and the best results belonged to the fixation of ZMB-Rim, and especially FZ-ZMB, Rim-FZ, and FZ-ZMB-Rim.

Conclusions: In patients with heavy masticatory forces, it is not recommended to use resorbable platesZygomatic fractures are the second most common facial injury, knowledge of their management is important. However, fixations methods, which are of importance are variable.

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

Introduction

Zygomatic bone fractures are the second most common facial trauma after nasal bone fractures, due to its prominent anatomy and its attachment to other facial bones.[1,2] Zygomaticomaxillary complex (ZMC) fractures refer to the bony fractures of the zygoma in 4 regions: the zygomaticomaxillary buttress (ZMB), the frontozygomatic (FZ) suture, the zygomaticotemporal suture, and the zygomaticomaxillary suture.[3] The displacement of the broken ZMC can lead to asymmetry, flattening of the zygoma, visual-ocular disorders, disruption of the dental occlusion, or limitation of opening of the mouth.[4]

The primary goal in treating bone fractures is to limit the extent of bone displacement to prevent complications such as lack of proper healing, infection, life-threatening abscesses, or functional dysfunctions.[5] In the past, wire fixation was used to treat the fractures of the zygomatic complex, but the results were not satisfactory.[6] In the last few decades, a wide variety of methods have been proposed to fix bone fragments.[1] Among the available techniques, the most appropriate and standard one is the use of internal fixation by a mini plate and screw,[7] which is widely used today.[2,4]

One of the main concerns of surgeons is the degree of stability of the method used for various plates.[8,9] Controversial findings are published on the degree of stability of plates in various fixation methods: Some authors prefer the 1-point method,[9,10] while others favor 2-point[11,12] or 3-point methods,[13] with some studies considering both 2- and 3-point methods similarly effective without any effects of the place of fixation.[14] Besides these, 4-point fixation has been as well suggested by some studies.[4,8] In a previous study, we assessed 1-point fixations

Finite element analysis (FEA) is a method to simulate the physics of materials and is broadly used to assess dynamics and behaviors of maxillofacial structures or treatment appliances under various loads and conditions existing dentistry.[15,16] This method can be used to measure the physical forces and movements of the ZMC fixed using different devices.[4] To our knowledge, except our recent simulation on 1-point internal fixations of ZMC,[4] no FEA studies testing structures that are relevant to clinical parameters of ZMC fracture and taking into account post-surgical occlusion forces has been reported in the literature. Moreover, the literature lacks any studies on the stability of many combinations of resorbable miniplates.

Objectives

Therefore, and considering the controversies over merits of different numbers and positions of fixation using plates,[1] we aimed to assess, for the first time, biomechanical patterns of different resorbable and non-resorbable 2-point and 3-point plates and their initial stability in treating fractures by finite element analysis.

Materials and Methods

The FEA model used in this study was based on the CT scan of a patient with a zygomatic bone fracture (taken retrospectively) selected from archived CT scans at a private radiology center. As selection criteria, a man about 30-40 years old, with linear fracture but without severe displacements and missing bone fragments and also without pathological, craniofacial, or occlusal problems before the injury was selected from the archive. University's review board approved the methods. Two maxillofacial surgeons and a computer engineer performed computer modeling and simulations. Mimics Innovation Suite V17.0.0.435 X64 Platform (Materialise, Leuven, Belgium) was used to model the CT slices (n=205, thickness=0.5 mm, format=DICOM) in Loss-less Compression mode. The model's accuracy was increased by constructing it in all three dimensions manually with a slice thickness of 0.5 mm. the cancellous and cortical bones were separated and the zygoma simulation was transferred to 3-Matic Research 9.0.0.231 (Materialise bv, Leuven, Belgium) for simulation of 3D geometrical solid surfaces. After reverse-engineering the fixation plates (thickness=2 mm) and placing them on the model using 6mm miniscrews (Jeil Medical Corporation, Korea). L-shaped 4-hole, curved 5-hole, 4-hole miniplates were used to fix the ZMB, infraorbital rim, FZ suture areas, respectively. Finite Element Abaqus (Dassault Systems, SolidWorks Crop, 2013) was used in the next step for mechanical analysis (with 241286 triangular volumetric elements and 483042 nodes) and estimating the linear displacement, rotational displacement, stress, and strain under physiological and severe mastication loads. Model parameters were as follows. Poisson coefficients: for resorbable screw and plaque (0.46), non-resorbable screw and plaque (0.33), and the bone (0.3): Modulus of elasticity: resorbable plate and plaque (3.15 GP), non-resorbable plate and plaque (105 GigaPascals), and the bone of (14.8 GigaPascals [GP]). After meshing, the force was exerted at the zygoma's center of gravity. The force was applied along the Z axis (perpendicular to the occlusal plane) and set at 150 and 750 N as normal and maximum occlusal loads.[17] Maximum and minimum extents of linear displacement, rotational displacement, stress, and strains were calculated and tabulated.[4]

Results

Displacement

Minimum displacement value for all fixation methods (non-resorbable, resorbable) and under either force (150 N and 750 N) was zero. In the non-resorbable group, under the 150N force, the maximum displacements of FZ-ZMB (frontozygomatic-zygomaticomaxillary buttress), Rim-FZ (Rim-frontozygomatic), ZMB-Rim (zygomaticomaxillary buttress-Rim), and FZ-ZMB-Rim (frontozygomatic-zygomaticomaxillary buttress-Rim) were respectively 0.123, 0.1649, 0.1757, and 0.117. In the non-resorbable group, under the 750N force, the maximum displacements of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.664, 0.8903, 0.9487, and 0.6317. In the resorbable group, under the 150N force, the maximum displacements of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.1166, 0.4786, 1.041, and 0.2544. In the resorbable group, under the 750N force, the maximum displacements of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 1.761, 2.584, 5.621, and 1.374. Non-resorbable fixations had much smaller displacements compared to their counterpart resorbable ones. Under the 150-N force, all non-resorbable categories showed minimal displacements. Among resorbable categories, the fixation of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim showed minimal displacements (Figures 1 to 4, Table 1). Under the 750-N force, among all resorbable and non-resorbable fixations, only the FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim fixations using non-resorbable fixations had minimal displacements (Figures 1 to 4).

Rotational displacement

Minimum rotational displacement value for all fixation methods (non-resorbable, resorbable) and under either force (150 N and 750 N) was zero. In the non-resorbable group, under the 150N force, the maximum rotational displacements of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.01704, 0.02285, 0.02246, and 0.0164. In the non-resorbable group, under the 750N force, the maximum rotational displacements of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.09204, 0.1234, 0.1267, and 0.08858. In the resorbable group, under the 150N force, the maximum rotational displacements of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.006536, 0.02681, 0.03794, and 0.01928. In the resorbable group, under the 750N force, the maximum rotational displacements of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.1104, 0.1448, 0.2049, and 0.1041. Resorbable fixations showed greater rotational displacements than non-resorbable ones. Under the 150-N force, resorbable and non-resorbable FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim categories had minimal rotational displacements. Under the 750-N force, among all resorbable and non-resorbable fixations, only the FZ-ZMB and FZ-ZMB-Rim fixations had somehow minimal rotational displacements.

Stress

Minimum stress value for all fixation methods (non-resorbable, resorbable) and under either force (150 N and 750 N) was zero. In the non-resorbable group, under the 150N force, the maximum stresses of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 187.9, 192, 192.7, and 155.7. In the non-resorbable group, under the 750N force, the maximum stresses of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 1015, 1037, 1041, and 840.5. In the resorbable group, under the 150N force, the maximum stresses of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 403.6, 230.2, 163.1, and 128. In the resorbable group, under the 750N force, the maximum stresses of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 791.2, 1243, 880.5, and 691.1. Stress was lower in non-resorbable types compared to their resorbable counterparts. Under both the 150N and 750N loads, the FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim had minimal stresses (either in the resorbable or non-resorbable).

Strain

In the non-resorbable group, under the 150N force, the minimum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively -0.00092, -0.00114, -0.00757, and -0.00088. In the non-resorbable group, under the 750N force, the minimum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively -0.005, -0.00613, -0.00409, and -0.00478. In the resorbable group, under the 150N force, the minimum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively -0.00057, -0.00302, -0.00231, and -0.00159. In the resorbable group, under the 750N force, the minimum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively -0.00874, -0.01628, -0.01246, and -0.0086. In the non-resorbable group, under the 150N force, the maximum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.002605, 0.004871, 0.006247, and 0.00233. In the non-resorbable group, under the 750N force, the maximum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.01407, 0.0263, 0.03373, and 0.0126. In the resorbable group, under the 150N force, the maximum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.009383, 0.03256, 0.01929, and 0.01501. In the resorbable group, under the 750N force, the maximum strains of FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim were respectively 0.08698, 0.1758, 0.1042, and 0.08107. Non-resorbable fixations showed much smaller strains compared to their counterpart resorbable ones. Under the 150N force, all non-resorbable fixation methods showed minimal strains; however, in the case of resorbable categories, the all evaluated cases had minimal strains. Under the 150N force, all non-resorbable categories showed minimal strains. Under the 750N force, non-resorbable categories had low strains, while resorbable methods had much higher strains; The FZ-ZMB and FZ-ZMB-Rim fixations had the lowest strains among the resorbable methods.

Table-1. Maximum and minimum of the stress, strain, displacement, and rotational displacement

			Strain		Stress		Displacement		Rotational displacement	
Type	**Force**	**Method**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
NR	**150 N**	**FZ-ZMB**	0.002605	-0.00092	187.9	0	0.123	0	0.01704	0
		Rim-FZ	0.004871	-0.00114	192	0	0.1649	0	0.02285	0
		ZMB-Rim	0.006247	-0.00757	192.7	0	0.1757	0	0.02246	0
		FZ-ZMB-Rim	0.00233	-0.00088	155.7	0	0.117	0	0.0164	0
	750 N	**FZ-ZMB**	0.01407	-0.005	1015	0	0.664	0	0.09204	0
		Rim-FZ	0.0263	-0.00613	1037	0	0.8903	0	0.1234	0
		ZMB-Rim	0.03373	-0.00409	1041	0	0.9487	0	0.1267	0
		FZ-ZMB-Rim	0.0126	-0.00478	840.5	0	0.6317	0	0.08858	0
R	**150 N**	**FZ-ZMB**	0.009383	-0.00057	403.6	0	0.1166	0	0.006536	0
		Rim-FZ	0.03256	-0.00302	230.2	0	0.4786	0	0.02681	0
		ZMB-Rim	0.01929	-0.00231	163.1	0	1.041	0	0.03794	0
		FZ-ZMB-Rim	0.01501	-0.00159	128	0	0.2544	0	0.01928	0
	750 N	**FZ-ZMB**	0.08698	-0.00874	791.2	0	1.761	0	0.1104	0
		Rim-FZ	0.1758	-0.01628	1243	0	2.584	0	0.1448	0
		ZMB-Rim	0.1042	-0.01246	880.5	0	5.621	0	0.2049	0
		FZ-ZMB-Rim	0.08107	-0.0086	691.1	0	1.374	0	0.1041	0

NR, Non-resorbable; **R**, Resorbable; **FZ**, frontozygomatic; **ZMB**, zygomaticomaxillary buttress; **Max**, maximum; **Min**, minimum.

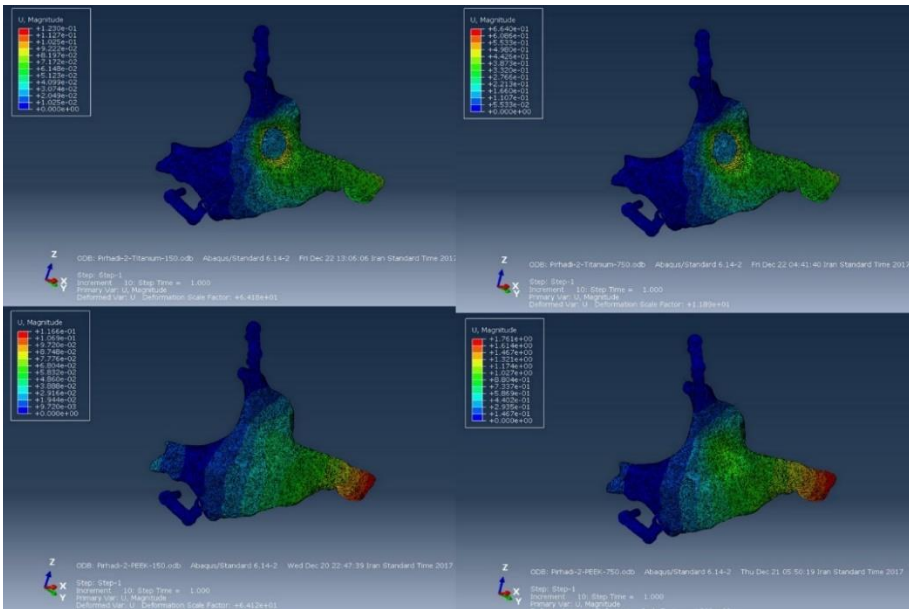

Figure 1. Displacement analysis of FZ-ZMB non-resorbable (top row) and resorbable (bottom row) models under the 150N force (left column) and 750N force (right column)

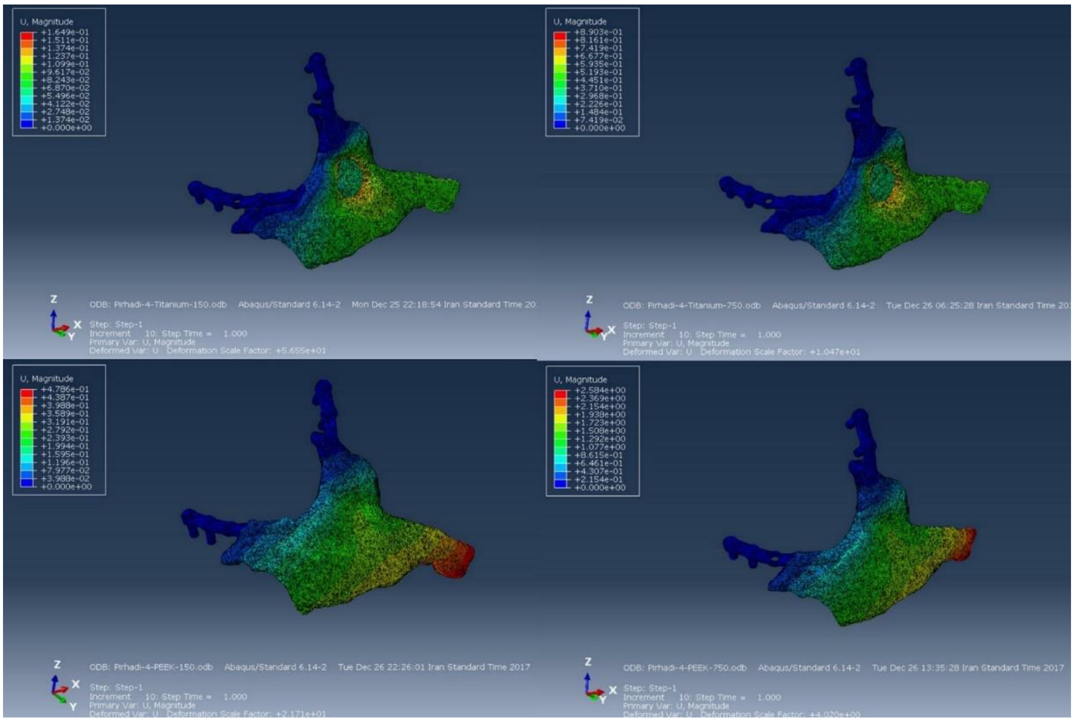

Figure 2. Displacement analysis of Rim-FZ non-resorbable (top row) and resorbable (bottom row) models under the 150N force (left column) and 750N force (right column)

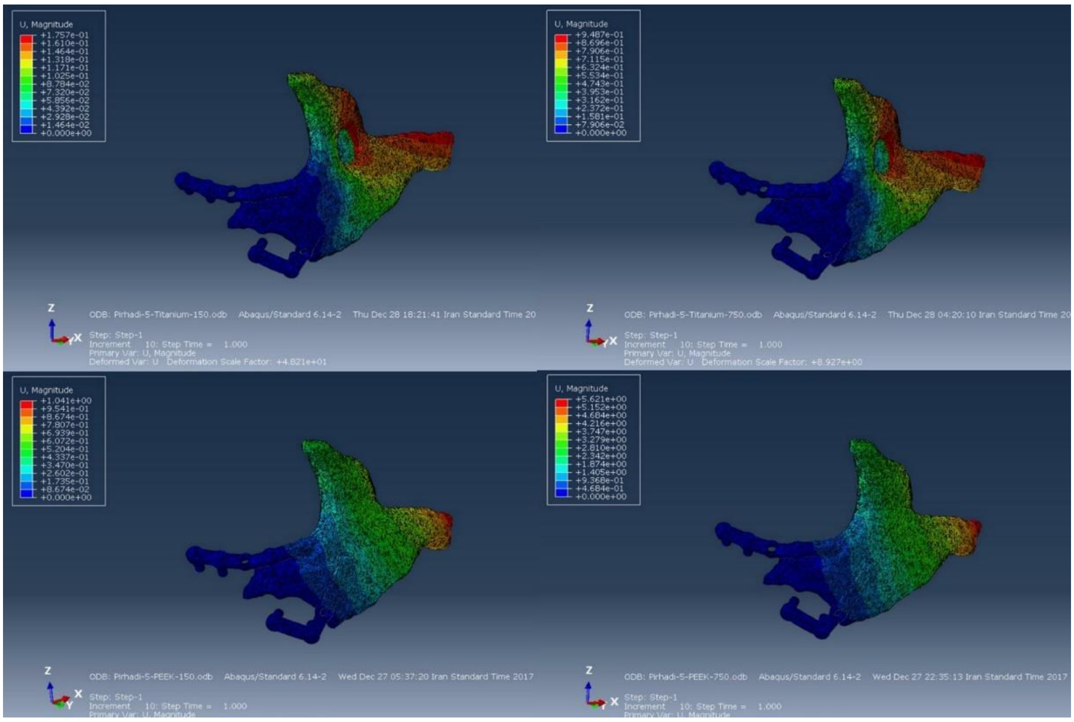

Figure 3. Displacement analysis of ZMB-Rim non-resorbable (top row) and resorbable (bottom row) models under the 150N force (left column) and 750N force (right column)

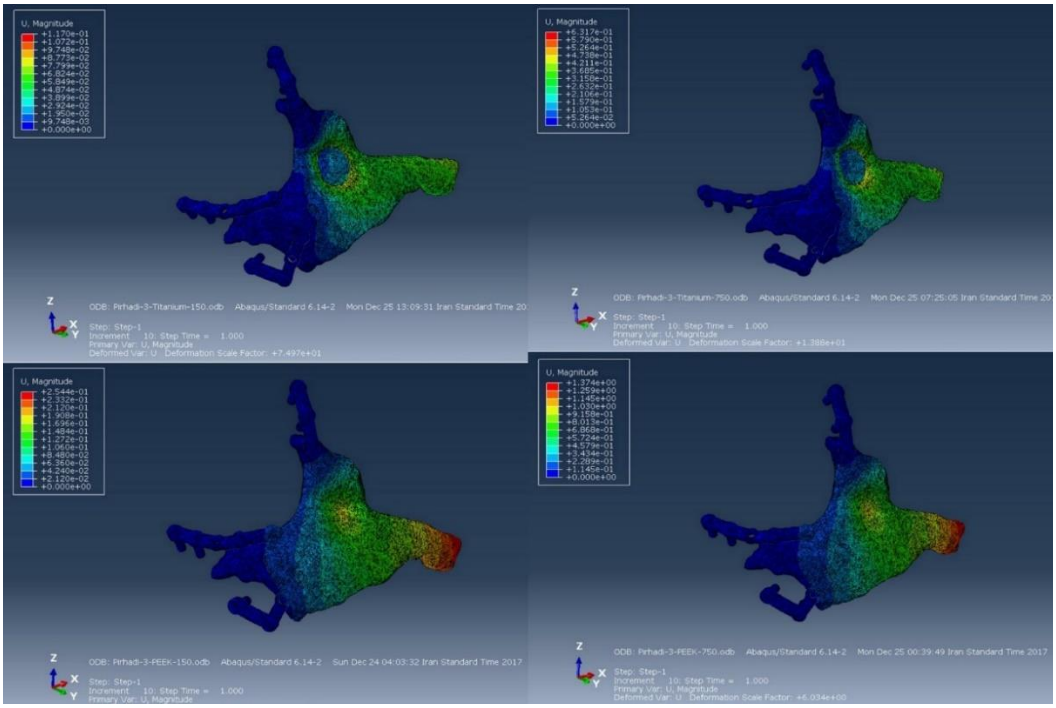

Figure-4. Displacement analysis of FZ-ZMB-Rim non-resorbable (top row) and resorbable (bottom row) models under the 150N force (left column) and 750N force (right column)

Discussion

Among fixation methods, the best one is the one that can cause minimum displacement and rotational displacement to ensure adequate initial stabilities.[4] There are various methods of internal fixation such as non-resorbable and resorbable systems, including the fixation using a mini-plate, which is basically a system of plates attached to the bone using the bone-screw joint.[4,7] Hence, the interaction of all three components (screw, plate, bone) determines the biomechanical function of fixation systems. The plate surface should conform on the bone surface, as this has a major role in the effectiveness of screw in attaching the plate to the bone.[4]

The best regions for 2-point fixation at 150 and 750 N was FZ-ZMB, which was in line with the results reported by Zachariadestet et al.,[18] Comparing the best 1- and 2-point fixation methods, both at 150 N and 750 N, the results showed that the FZ-ZMB fixation had a lower rate of displacement in the 2-point method. Kim et al. [10] compared patient satisfaction towards the fixation in ZMB versus FZ-ZMB.[10] Although the stability was not assessed biomechanically, patients were satisfied with the relative stability. As a result, the basis for the score was evaluated based on the amount of scarification, which was reported less in the ZMB group.[10] On the other hand, Praveen and Parmar stated that 1-point fixation in the ZMB was appropriate only when the fragments do not move after the fixation; otherwise, a 2- or 3-point fixation would be suggested.[19]

In the results obtained from this study, the best fixation was achieved with the 3-point method under both 150 and 750 N loads. In this regard, Arora et al.,[20] pointed out that the 3-point method is not significantly different from the 2-point method (FZ-ZMB) in terms of stability, but complications of 3-point procedure can include greater scars due to additional surgeries due to rim fixation.[20] Davidson et al.,[6] concluded that fixation by the 1-point method might not provide sufficient stability; the 2-point method is a suitable option for fixation, but they proposed the 3-point method for achieving maximum stability.[6] Lee et al.,[11] compared the two-point and 3-point methods, and found the 3-point fixation a better methods.[11] Also Punjabi SK et al.,[21] and Parashar et al.,[22] preferred the 3-point method because of its superior stability compared to other fixation methods. Comparing the 2- and 3-point fixation methods in the present study, it can be concluded that under the 150-N load, an appropriate method could be the 2-point fixation at FZ-ZMB regions, while under the 750-N load, the 3-point fixation could be the best approach. Nasr et al.,[23] as well compared the 3- and 2-point fixations (in ZMB-Rim areas) and asserted that both were clinically acceptable, but in terms of displacement, the 3-point option was more appropriate.[23]

Our previous study had assessed other methods such as frontozygoma region fixation and had found it as the best fixation for performing 1-point fixation at 150 and 750 N.[4] In line with our earlier findings, other studies as well stated that frontozygomatic is the best 1-point fixation method that provides proper stability.[12] However, Sridhar et al [24] did not find a significant difference between fixation of frontozygomatic and zygomaticomaxillary buttress, in terms of stability and function. But the function and stability are not the only factors to be considered; better reduction and sight, more convenient access, and lower scarification are other options that make zygomaticomaxillary buttress fixation a proper method.[4,10]

Since dynamics and stability of resorbable plates had not been assessed (except in a recent paper on 1-point fixations),[4] we investigated these as well. Resorbable internal fixations might have some advantages such as proper stability (indicated by clinical studies);[25,26] they may have fewer complications than non-resorbable systems[27] and can have unique chemical and physical properties [28] which mark them as proper alternatives for non-resorbable systems.[4,13,29-31] However in laboratory assessments, the displacement of resorbable fixations might be more significant than that of non-absorbable ones, because resorbable polymers have lower moduli of elasticity.[4,32,33]

A number of limitations constrained the present study. Firstly, in silico studies cannot be generalized to the population, because they lack statistical measures needed for conclusions based on statistical substantiation. They are merely models of one person. It is not known what values would have been obtained if the model had been built on a CT scan of another person. A woman could have a completely different bone structure compared to a man, and age would matter as well. hence, future studies should confirm or reject our results through proper animal and human designs and implementations in order to test if the types recommended in this study act better in the real bone structures or not. Such studies need to be balanced in terms of the age of involved patients and their gender distributions, so that confounding factors be minimized. Furthermore, although 3D simulating software are state-of-the-art devices to measures and simulate forces and material reactions, they can never really simulate the intricate molecular arrangements within the metals or plastics used or within bones or soft tissues under surgery. This might be more and more trivial in the future, when the computational power increases and the simulation accuracy increases correspondingly. But even in the future with proper computational powers, one cannot know microscopically the properties of solids under simulation; we can just estimate certain averages for macroscopic regions and materials, and not for microscopic elements. We tried to improve our study results by using various fixtures and two different force extents, so that diversity of results can offset for the limitations of this method. However, we could also use more combinations in order to assure the best amount of diversity. On the other hand, computerized 3D simulations allow a great degree of insight into the workings of the dental material as well as the forces and even slight deformations possibly imposed on the bone and soft-tissue structures. This is impossible with any other method. Finally, this 3D finite element analysis method only estimates the short-term changes and forces and cannot estimate long-term changes or success rate. Future clinical studies are needed to examine the success and complications of each of these systems in long-term and from a clinical point of view. Besides this, future finite element analyses are helpful in understanding the behavior of more combinations of fixation systems, especially on men and women separately and on different age ranges separately. In this study and our previous one, we assessed resorbable internal fixation methods because clinical evidences suggest that they are properly stable [25,26] and because there was no study on their biomechanical behavior.[4] Moreover they can have other desirable features such as unique physical and chemical properties [28] and fewer complications in comparison to the non-resorbable fixation plates.[4,13,27,29-31] Resorbable systems have a behavior of an elastic-viscous type and their flexibility is approximately 10 times greater compared to non-resorbable devices.[4,28] However, resorbable fixation devices can come with their own complications such as mobility and foreign body reactions and mobility; still, their complications are not usually as significant in bilateral sagittal split osteotomy, bimaxillary operations, and Le Fort I operation.[4,34] The movement of resorbable cases can be more noticeable in vitro than non-resorbable ones, because the modulus of elasticity of resorbable polymers is closer to that of the bone, being less than that of the non-resorbable types.[4,32,33] Utilization of metal plates can cause complications including being palpable under the skin, post-corrosion inflammation, screw loosening, pain, sensitivity to temperature, interference on radiographs and superimposition on bony structures, needing for a secondary surgery in order to remove them, and constraining the growth of children's bones.[4,35]

Conclusions

As expected, maximal loads would cause more displacements and stresses regardless of the used combination of fixations. The stability of resorbable 2- and 3-point fixations (regardless of the combination in use) would be usually lower than the stability of the same combination of fixations but non-resorbable. Although 3-point fixation methods yielded subtly better results than the 2-point fixation of FZ-ZMB, their need for an extra surgery bearing extra pain, scars, and expenditures compared to FZ-ZMB should be considered while choosing for the method of fixation. Again, the reduced procedures of resorbable mini-plates can be considered an advantage, when the selected fixation method can provide minimal displacements (e.g., FZ-ZMB, Rim-FZ, ZMB-Rim, and FZ-ZMB-Rim under normal occlusal load but not under heavy loads). Clinical experiments are needed to verify these deductions. Future clinical studies are warranted to verify our results though long-term success of these systems.

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None.

Authors' Contribution

All authors pass the four criteria for authorship contribution based on the International Committee of Medical Journal Editors (ICMJE) recommendations.

Conflict of Interests

The authors declared no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

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