RESEARCH

A Comparison of Titanium and Resorbable Miniplate Systems Using Finite Element Analyses with the Orthotropic Mandibular Model in Condyle Fracture

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ABSTRACT

A Comparison of Titanium and Resorbable Miniplate Systems Using Finite Element Analyses with the Orthotropic Mandibular Model in Condyle Fracture

Background: Mandibular fractures comprise a large portion of facial injuries. According to comprehensive series published, 17.5 - 52% of mandibular fractures are condyle fractures. With the development of plate and screw systems, open reduction and internal rigid fixation have also become methods that are accepted. Titanium miniplate and screw systems or resorbable plate and screw systems are used for this purpose. The purpose of this study is to compare the superiorities of titanium plate and screw systems to the superiorities of resorbable plate and screw systems on an orthotropic mandibular model using the finite element analysis (FEA) method.

Methods: With finite element analysis, stress values in bone, plate and callus and the amount of displacement in plates and fragments with Von Mises forces were examined.

Results: It was observed that solitary resorbable plates do not generate adequate stability.

Conclusion: It was observed that titanium plate and screw systems were mechanically superior to resorbable plate and screw systems in the open treatment of mandibular condyle fractures. However, to fully support this opinion, studies with different designs using new resorbable plates are required.

KEYWORDS

Biomechanical Tests, Condyle Fractures, Finite Element Analyses, Resorbable Plate Systems, Titanium miniplates

ÖZ

Kondil Kırıklarında Ortotropik Mandibula Modeli ile Sonlu Eleman Analizleri Kullanılarak Titanyum ve Rezorbe Olabilen Miniplak Sistemlerinin Karşılaştırılması

Amaç: Mandibula kırıkları, yüz yaralanmalarının büyük bir bölümünü oluşturur. Yayımlanan kapsamlı serilere göre, mandibular kırıkların% 17.5-52'si kondil kırıklarıdır. Plak ve vida sistemlerinin geliştirilmesi ile açık redüksiyon ve internal rijit fiksasyon geniş kabul gören bir yöntem haline gelmiştir. Bu amaçla, titanyum miniplak ve vida sistemleri veya rezorbe olabilen plak ve vida sistemleri kullanılmaktadır. Bu çalışmanın amacı, ortotropik olarak elde edilen mandibula modelinde, titanyum plak ve vida sistemleri ile rezorbe olabilen plak ve vida sistemlerinin, kondil kırıklarında kullanımını, sonlu eleman analizi (FEA) yöntemi ile karşılaştırmaktır.

Gereç ve Yöntemler: Sonlu elemanlar analizi ile kemik, plak ve kallusda oluşan stres değerleri ve Von Mises kuvvetleri ile plak ve fragmanlardaki yer değiştirme miktarı incelenmiştir.

Bulgular: Mandibular kondil kırıklarında, rezorbe olabilen plakaların oluşan kuvvetlere karşı yeterli stabilite oluşturmadığı gözlenmiştir.

Sonuç: Mandibula kondil kırıklarının açık tedavisinde titanyum plak ve vida sistemlerinin, rezorbe olabilen plak ve vida sistemlerinden mekanik olarak üstün olduğu gözlenmiştir. Bununla birlikte, bu görüşü tam olarak desteklemek için, farklı tasarımlarla üretilmiş yeni rezorbe olabilen plakların kullanıldığı çalışmalar gerekmektedir.

ANAHTAR KELİMELER

Biyomekanik testler, Kondil kırıkları, Sonlu eleman analizi, Rezorbe plak sistemi, Titanyum miniplaklar

Mandibular fractures comprise a large portion of facial injuries. According to comprehensive series published, 17,5-52% of mandibular fractures are condyle fractures.[1–9] Currently, the treatment of mandibular condyle fractures continues to be the most debated subject of maxillo-mandibular trauma.[9–12]

Treatment options can be described as closed reduction and open reduction. With the development of plate and screw systems, open reduction and internal rigid fixation have also become methods that are accepted and more used. Zide, has stated two definite indications for open reduction of condyle fractures such as displaced condyle and cases where it is unable to preserve the ramus neck.[11] These indications, introduced in the mid-1980s, were determined according to the technological possibilities of that period. However, with developing technology open reduction techniques are used more often.[9]

Titanium plate and screw systems are often preferred because of high tissue compatibility, easily shaped, and provides adequate rigidity and force. One of the disadvantages of titanium plates, is that they act as a shield against stress inflicted on the area they are applied to and so they gradually cause bone resorption and atrophy. Besides this, the most common problems reported after using titanium are infection, pain, swelling, thermal sensitivity, and loosening or loss of the plate and screw system. The most common reason of the loosening of the plate and screw system is infection.[12–16] Due to these complications or by request of the patient the titanium plate and screw system might have to be

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removed.[16–18]

Due to the complications of titanium, plate and screw systems containing a strong absorbable polymer poly-L-lactic acid (PLA), polyglycolic acid (PGA), and polydioxane (PDS), or combinations of these materials have been introduced. These materials start to be resorbed by the body depending on their chemical properties after they are inserted surgically.[19] There is limited evidence about a foreign body reaction due to prolonged resorption rate. The modulus of elasticity of resorbable plate and screw systems is closer to that of bones in comparison to other materials and therefore they do not form a stress shield like titanium systems. Thus, they do not cause atrophy in the fracture area either. The most important concern about resorbable materials are whether they have adequate rigidity and resistance or not.[20,21]

The finite element analysis (FEA) is a system used to transfer the biomechanical characteristics of bone tissue into a limited virtual environment by means of a specific numerical method. Meyer et al. (2000), identified a high correlation between in vitro mandibular measurements performed using this method.[22] Although this method does not report definite verdicts, it provides a detailed explanation of the distribution and associations of the stress and forces generated on the bone specimen. The FEA method is often used to test the reliability of fixation, and the forces and features of the material used can be changed using this method.[23]

This study is based on the hypothesis that resorbable plate and screw systems that have biological advantages over titanium miniplates and screws can be used in the treatment of mandibular condyle fractures instead of titanium plate and screw systems.

The purpose of this study is to compare the superiorities of titanium plate and screw systems to the superiorities of resorbable plate and screw systems on an orthotropic mandibular model using the finite element analysis (FEA) method.

MATERIALS AND METHODS

Modelling and Geometric Configuration

The digital volumetric computed tomography (DVCT) data of a 25-year-old healthy male with full dentition and Angle Class I occlusion obtained for diagnostic purposes were used in the finite element analysis. The Digital Imaging Communications in Medicine (DICOM) data obtained from the DVCT were transferred into MIMICS (Materialise, Medical Software, Leuven, Belgium) and 3-D modelling was performed. A 0.3 mm thick subcondylar fracture line was created on this model. The resorbable plates and screws and the titanium plates and screws were modelled three-dimensionally using AutoCAD (Autodesk Inc., PA, USA) (Figure 1). These models were applied onto the fracture line, similar to clinical practices used to fixate the fracture (Figure 2).

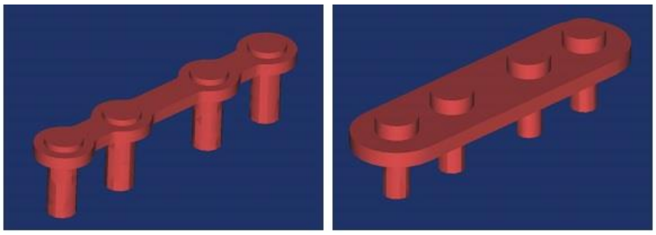


Figure 1

3D modeling of the resorbable and the titanium plate screw systems. 154x53mm (300 x 300 DPI)

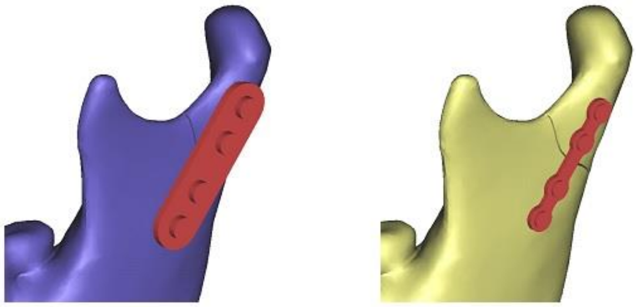


Figure 2

Resorbable and titanium plate and screw systems placed in the mandible model. 137x68mm (300 x 300 DPI)

The model created was later transferred into the ANSYS (ANSYS, Inc. PA, ABD) software. Using this software, the finite elements, and the mesh that binds them were created using a three-dimensional model (Figure 3). Because the enamel is insignificant with respect to the transmission of force in finite element analyses, the dentin structure with a high modulus of elasticity was modelled.[24] The structures that demonstrated different elastic modulus characteristics such as the cancellous bone, cortical bone, dentin material, primary callus were defined on the three-dimensional model. The model created was re-transferred to MIMICS once more. The cortical and cancellous bones do not have the same thickness and modulus of elasticity throughout the mandible. To obtain a more realistic and homogeneous three-dimensional model, the cortical bone was separated into eight different structures, the cancellous bone was separated into two different structures based on Hounsfield Units (HU), and this separated model was transferred into ANSYS once again. A mesh was formed from all of the structures formed using tetrahedral solid elements. Finally, the mandibular model fixated using titanium plates consisted of 129224 elements and 194527 knots, the model fixated

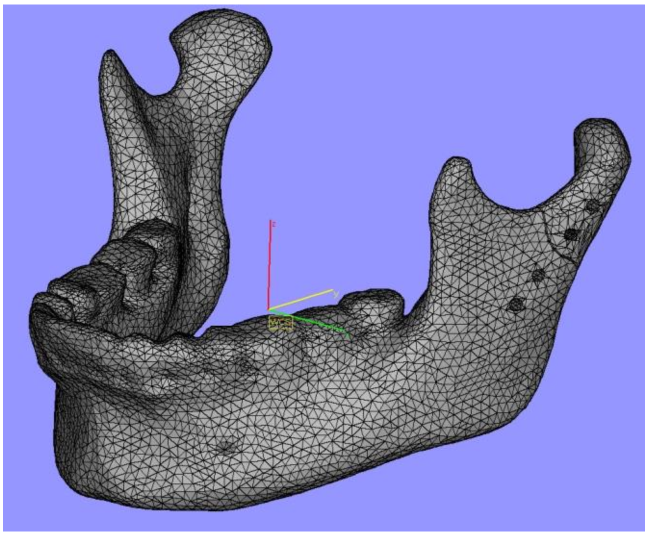


Figure 3

Mesh structure created from nodes and elements in the 3D mandible model. 256x222mm (300 x 300 dpi)

with resorbable plates consisted of 121690 elements and 182579 knots. The coordinate system is shown in Figure 4.

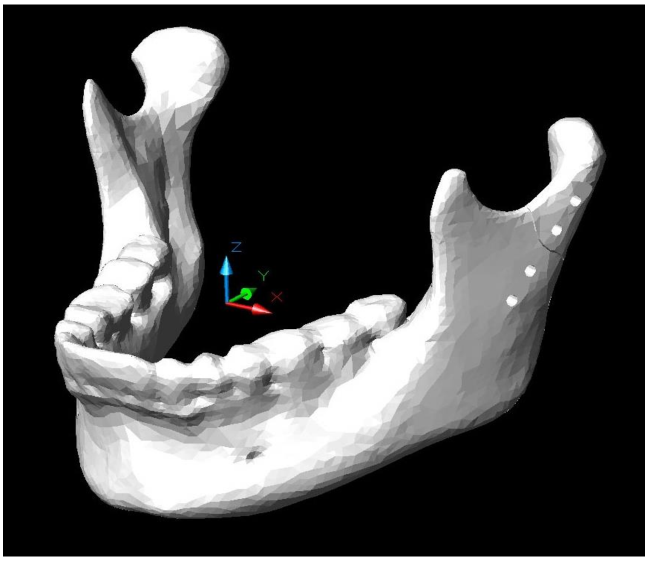


Figure 4

Created 3D mandible model and coordinate system. 228x205mm (300 x 300 DPI)

Characteristics of the Material

The attachment localizations of the masticatory muscles were designed by using anatomical data on the three dimensional model 25 and were application was done according to the vectors and forces reported by Koiroth et al. 24 (Table 2) (Figure 5). The model was limited by two means. In the first application, it was limited except the x-axis rotation allowing only opening and closing movements in the joint. This limitation was applied allowing mandibular movements of the rigid temporal bone 24,26–28. In the second application, the condyle was limited in all directions, and the molar biting force of 200 N on the opposite side was evaluated.

Table 2.

Muscles, Muscle Forces, Vectors Coordinates of Muscles and Number of Nods WS; Worked Side, BS; Balanced Side

		Scaling Rates		Vector Coordinates			
Muscles	Muscle Forces (N^2)	Righ t/WS	Left/ BS	x	y	z	Number of Nods
M. Masseter Pars Superficialis	190,4	0,72	0,6	-0,207	0,885	0,419	248
M. Masseter Pars Profunda	81,6	0,72	0,6	-0,546	0,758	-0,358	271
M. Pterygoideus Medialis	174,8	0,84	0,6	0,486	0,791	0,372	312
M. Temporalis anterior	158	0,73	0,58	-0,149	0,988	0,044	333
M. Temporalis middle	95,6	0,66	0,67	-0,221	0,837	-0,5	255
M. Temporalis posterior	75,6	0,59	0,39	-0,208	0,474	-0,855	335
M. Pterygoideus lateralis inferior	66,9	0,3	0,65	0,63	-0,174	0,757	65

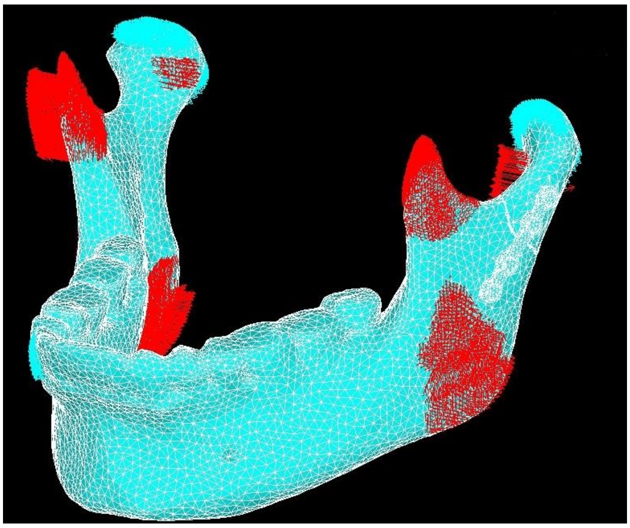


Figure 5

Muscle insertion areas and pull vectors of muscles applied in 3D model. 205x170mm (300 x 300 DPI)

Evaluation

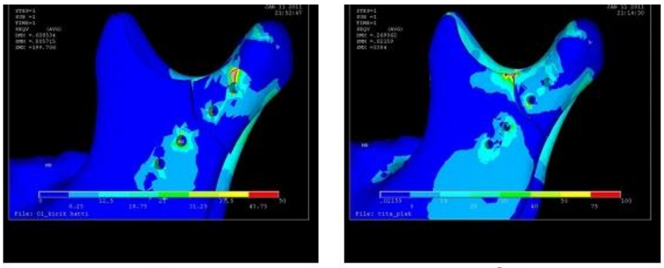
The finite element analyses were performed for situations in which the total muscle force applied closed the mandible, and when a 200 N force of molar biting was applied on the opposite side and was evaluated according to the following criteria:

1. The examination of the Von Mises forces in the bone in the region of the fracture
2. The examination of the Von Mises forces of the plates
3. The amount of displacement in the plates
4. The amount of displacement in the fragments
5. The Von Mises forces formed in the callus

The stresses and displacements formed in the model were evaluated using figures and charts.

RESULTS

The maximum Von Mises force in the cortical bone during mandibular closing movements was found to be 3304 MPa in the model with titanium plates and screws and to be 200 MPa in the model with resorbable plates and screws. The minimum Von Mises forces were found to be 0,0215 MPa in the titanium plate and screw model, and to be 0,00571 MPa in the resorbable plate and screw model. The average Von Mises values surrounding the screws was found to be 12 MPa in the titanium plate and 9.5 MPa in the resorbable plate (Figure 6).



a b

Figure 6

Stresses in the bone applied with titanium plate-screws system during the 200N biting force from the molar region. b) Stresses in the bone applied with resorbable plate-screws system during the 200N biting force from the molar region. 149x62mm (300 x 300 DPI)

When a 200 N force was applied during molar biting in the opposite side, the Von Mises maximum force was 3438 MPa in the model that used titanium plates and screws and it was 235 MPa in the model that used resorbable plates and screws. The minimum Von Mises forces were found to be 0,00482 MPa in the titanium plate and screw model, and to be 0,0085 MPa in the resorbable plate and screw model. When a 200 N force was applied during molar biting on the opposite side, the mean Von Mises forces surrounding the titanium plates was 11 MPa and the forces surrounding the resorbable plates was 13 MPa (Figure 7).

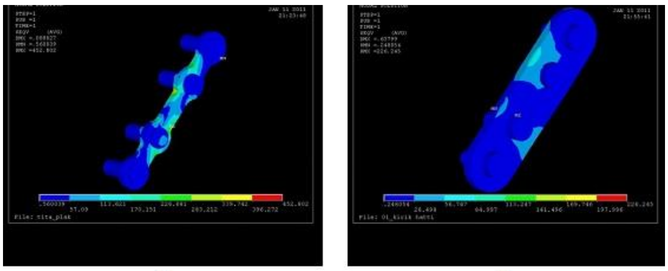


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Figure 7

Stresses in the plate applied with titanium plate-screws system during the 200N biting force from the molar region. b) Stresses in the plate applied with resorbable plate-screws system during the 200N biting force from the molar region. 146x61mm (300 x 300 DPI)

The Stress Values of the Plates

The maximum Von Mises force generated during mandibular closing movement was found to be 453 MPa in the titanium plate and to be 226 MPa in the resorbable plate. The minimum Von Mises force generated during mandibular closing was 0.56 MPa in the titanium, and it was 0.248 MPa in the resorbable plate (Figure 8).

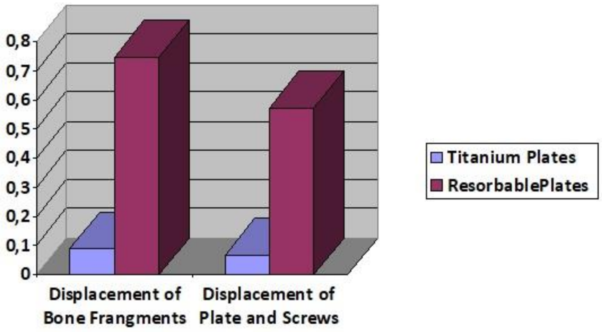
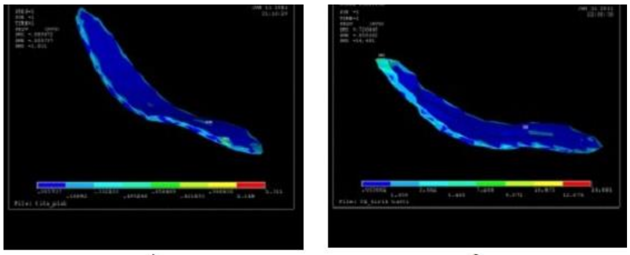


Figure 8

Displacement in plates and bone fragments at 200 N molar bite. 149x80mm (300 x 300 DPI)

When a 200 N force was applied during molar biting on the opposite side, the maximum Von Mises force was 489 MPa in the titanium, and 267 MPa in the resorbable plate. The minimum Von Mises force was 0.6072 MPa in the titanium, and 0.2788 in the resorbable plate (Figure 9).



A b

Figure 9

a) Distribution of stresses in the callus in the model fixed with titanium plate-screws system during the 200N biting force from the molar region. b) Distribution of stresses in the callus in the model fixed with resorbable plate-screws system during the 200N biting force from the molar region. 148x63mm (300 x 300 DPI)

The Mobility of the Bone Fragments and Plates

The titanium plate moved by 0.088 mm during mandibular closing, and the resorbable plate moved by 0.063 mm. During mandibular closing, the bone fragments moved by 0.0701 mm in the titanium plates and by 0.485 mm in the resorbable plates model (Figure 10).

The displacement generated in the titanium plate was 0.07 mm and 0.57 mm in the resorbable plate during molar biting of a force of 200 N on the opposite side. The displacement of bone fragments was measured as 0.09 mm in titanium, and 0.75 mm in the resorbable plates (Figure 11).

The Stress Values of the Callus

The maximum Von Mises force generated in the callus during mandibular closing movements was 1.3 MPa in the model using titanium plates and screws, and it was 1.3 MPa in the model used resorbable plates and screws. The minimum Von Mises forces were found to be 0,006 MPa in the titanium plate and screw model, and to be 0,005 MPa in the resorbable plate and screw model. The average Von Mises force in the model where titanium plates and screws were used was 0.12 MPa, and it was 1.3 MPA in the model where resorbable plates and screws were used (Figure 12).

During molar biting of a 200 N force on the opposite side, the Von Mises maximum stresses generated on the titanium plate model was 1.3 MPa and it was 15 MPa for the resorbable plate model. The minimum Von Mises stresses for the titanium plate, and screw model was 0.005 MPa and it was 0.05 MPa for the resorbable plate model. The average Von Mises stress generated in the callus was 0.13 MPa for the titanium plate model, and it was 1.48 MPa for the resorbable plate model (Figure 13).

The results obtained during mandibular closing are presented in Table 3, and the results obtained when 200 N molar force was applied on the opposite side are presented in Table 4.

Table 3.

During mandibular closing, the amount of displacement of plates and bone fragment and Von Mises values of the plate, primary callus and bone

	Displacement (mm)		Von Mises Values (MPa)				
			Plate		Primary Callus		Bone
	Plate	Bone Fragments	S_{min}	S_{max}	S_{min}	S_{max}	S_{mean}
Titanium Plate	0,088	0,0701	0,56	204	0,006	1,3	12
Resorbable Plate	0,637	0,485	0,248	239	0,05	1,3	9,5

Table 4.

During 200 N molar force was applied on the opposite side, the amount of displacement of plates and bone fragment and Von Mises values of the plate, primary callus and bone

	Displacement (mm)		Von Mises Values (MPa)				
			Plate		Primary Callus		Bone
	Plate	Bone Fragments	S_{min}	S_{max}	S_{min}	S_{max}	S_{mean}
Titanium Plate	0,07	0,09	0,6072	489	0,0048	1,3	11
Resorbable Plate	0,57	0,75	0,2788	267	0,05	15	13

DISCUSSION

Mandibular condyle fractures are the most common injury type among facial injuries.[29] The treatment of condyle fractures is one of the most debated subjects among maxillofacial traumas. With the introduction of new techniques, the superiorities of treatment modalities over each other have been examined, and new indications and contraindications have been reported based on this findings.[30] Zide, has stated that the two definite indications for open reduction of condyle fractures are displaced condyle fractures and inability to preserve the ramus neck.[31] With the development of new fixation materials and techniques, and also approaches such as endoscopy that minimize anatomical risk open reduction and rigid fixation have become preferred options.[32]

Before clinical application, both metal alloys and resorbable plates require being tested in vitro to determine the physical characteristics and the methods of use of the newly developed material. These test methods are conventional biomechanical experiments and FEA. Conventional biomechanical experiments are conducted using real specimens or specimens resembling real specimens. FEA is an analytical method based on numerical data that makes it possible to analyze the forces applied to the craniofacial skeletal structure in three-dimensional space and the response generated to this force.[33] FEA is a valid and non-invasive method, and it is very suitable for analyzing the complex biomechanical behavior of the human mandible.[27,34] Finite element analysis is an alternative to measurements done using strain gauges that is performed in a virtual environment.[13,30] The area and number of the regions where stress measurements are performed depend on the size of the stress gauge, and a limited amount of data can be obtained. However, in FEA, the stresses at any point of the entire model can be analyzed.

Most of the previous FEA studies considered the mandible to be isotropic and homogeneous.[13,26,33] Isotropy is a biomechanical term expressing that the forces applied to one region are distributed evenly in every direction. However, ultrasonographic studies have shown that the mandible is not isotropic, it is orthotropic.[35] Unlike many other studies, our finite element analysis modelled the mandible with orthotropic characteristics. This was facilitated by creating different areas of the mandible at different thicknesses and by setting different modulus of elasticity and Poisson's ratios in correlation with bone density based on HU.

Condyle fractures are more common in men between the ages of 21 and 30.[1] It is for this reason, we especially used the DVCT data of a 26-year-old male. The condyle fracture was also formed on the left side because condyle fractures were more common on the left side in literature.[1]

Many studies have used the same modulus of elasticity for all regions of the cortical bone.[13,23,33] By this means, the three-dimensional model with a complex geometry gains isotropic characteristics. In our study, a single modulus of elasticity value was not given for the cortical bone. Depending on the material density in the DVCT values, the software split the cortical bone into 8 and the cancellous bone into 2 separate structures, and the moduli of elasticity were distributed in correlation with HU values for this different material. By means of this method, the mandible can be modelled orthotropically, and a more realistic distribution of force can be facilitated.

It literature it has been reported that muscular activity is approximately 60% of normal levels during the first six weeks after condylar and angular fractures.[36,37] According to this knowledge, we also took into account 60% of the adult molar biting force which is 200 N, as the evaluating biting force. In the study they conducted, Throckmorton et al. (2004) reported that the masseter electromyography (EMG) activity of the fractured area was at normal levels during molar biting, but that the masseter EMG was 1.5 more active during molar chewing on the opposite side.[38] Therefore, the molar region opposite the side of the fracture was taken as the biting and occlusal reaction area.

In a study conducted on a sheep model, Von Mises stresses higher than 0.15 MPa prevent intraosseous ossification and lead to endochondral healing.[39] In our finite element analysis study, the average stress generated was 0.13 MPa in the model fixated with a titanium plate during molar biting of the opposite side with a force of 200 N, and the average stress of the resorbable plate was 1.48 MPa. According to these results, during 200 N molar biting in the opposite side, the fixation of the titanium plate is within biological range, but the stress generated in the callus of the model fixated with resorbable plates is above the normal limit.

The stress values that cause permanent destruction are important parameters when evaluating the durability of the material under stress.[40] The American Society for Testing and Materials has reported this stress value between 275 and 450 MPa for second-degree titanium plates and, as 233 MPa for resorbable plates. http://www.inion.com/about_inion/en_GB/white_papers/_files/77769175585587764/default/Inion OTPS FreedomPlate white paper.pdf According to the finite element analysis, the stress on the titanium plate was measured as 489 MPa and as 267 MPa on the resorbable plate during molar chewing at a force of 200 N on the opposite side. According to these results, enough stress to cause permanent deformation will build up on both materials during opposite side molar chewing with a force of 200 N.

According to the FEA results, the fracture fragments moved by 0.09 mm in the model fixated with titanium and by 0.75 mm in the model fixated with resorbable plates during 200 N opposite side molar biting. In an animal study, it was reported that the mobility of bone fragments should be between 0.15 and 0.5 mm to facilitate bone healing.[41] According to these results, while titanium plate fixation allows movements within biological limits, resorbable plates cause much more mobility.

According to the results of the FEA, the stresses generated throughout the mandible are significantly high in both groups. However, these results can be attributed to the geometric structure formed as a result of modelling. The sharp edges of the elements that compose the model may lead to high tensile forces. For a healthier evaluation, the midpoints of the elements surrounding the screws were also evaluated. When the distribution of all forces was taken into consideration, the titanium plates provided a more rigid fixation than resorbable plates, and in general, they provided better stress distribution. Titanium plates absorb the forces inflicted and transfer less stress to the bones they are in contact with. Thus, the stresses accumulate on the titanium, and excessive stress that could lead to the loss of a screw is prevented. In resorbable plates, forces applied can easily deform the plate and more force is transmitted to the bone.

Because we were only able to test a single resorbable plate in our study due to anatomical difficulties, the results may have favored the titanium plate. In a study conducted that resorbable plates with different designs can provide adequate fixation and that solitary resorbable plates yield the most unsuccessful results among these designs.[42]

CONCLUSION

Finally, it was observed that titanium plate and screw systems were mechanically superior to resorbable plate and screw systems in the open treatment of mandibular condyle fractures. However, to fully support this opinion, studies with different designs using new resorbable plates are required.

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