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Original research

Comparison of screw and plate osteosynthesis in advancement genioplasty: a finite element analysis study

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Purpose

The purpose of this study was to evaluate the distribution of stresses in screw and plate fixation systems during simulated advancement genioplasty using finite element analysis.

Materials and Methods

A cone-beam computed tomography image of a patient was used to create three-dimensional virtual models of mandibular bone. Chin advancement of 8 mm was simulated following a horizontal osteotomy of the chin in a computer-aided design program. The distal segment was stabilized with two titanium mini-screws placed bilaterally in the first model and a single 4-hole titanium pre-bent chin plate placed centrally in the second model. The plate was fixed with four mini-screws, two in the proximal and two in the distal segment. All fixative appliances were submitted to 15 N force applied backwards to the lingual surface of the chin parallel to the occlusal plane and 7 N force applied upwards to the buccal surface of the chin perpendicular to the occlusal plane. The distributions of von Mises stresses and deformations in bone and titanium materials were evaluated.

Results

In the screw fixation system (22.52 MPa) higher stress values were observed compared to the plate fixation system (13.71 MPa). The deformation value was higher for the screw fixation system (0.021 mm) than the plate fixation system (0.0007 mm).

Conclusion

In advancement genioplasty, fixation with a single pre-bent centrally placed chin plate showed slightly better stabilization than fixation with two bilaterally placed bicortical screws. The stress values were within the physical strength limits of bone and titanium for both systems.

Keywords: *Genioplasty, bone plate, bone screw, finite element analysis, stress distribution*

Introduction

The chin plays an important role in facial aesthetics and overall appearance and creates the basis for judging an individual's character (1). A properly shaped and positioned chin contributes to self-confidence and good social life (2).

Genioplasty is a surgical procedure performed to correct the cosmetic deformities of the chin in three dimensions and has been carried out alone or in association with other orthognathic surgical procedures (3). Hofer (4) first described the horizontal sliding osteotomy of the anterior half of the inferior border of the mandible performed by a submental approach to the chin in 1942. Trauner and Obwegeser (5) first described the intraoral approach to expose the symphysis for horizontal osteotomy of the chin in 1957. Over the years various modifications have been de-

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scribed to lengthen, shorten, advance, set back, widen, or narrow the chin.

Among all movements of the chin, the most frequently performed is the advancement genioplasty (2). Advancement genioplasty is a reliable surgical procedure however; suprahyoid muscles and perimandibular connective tissues attached to the mandible can contribute to mechanical instability and relapse by creating resistance during advancement (1,3). Therefore, the use of a proper fixation technique is important for predictable postoperative results. Today, rigid internal fixation with plates or screws is the standard procedure because of their ease of application and reliability (6-9).

Various studies were conducted to evaluate the most reliable fixation method in terms of skeletal and soft-tissue stability in genioplasty procedures (7-15), however, the discussion about the ideal type of fixation is still going on (16). To our knowledge, the stability of titanium bicortical screw and plate fixation systems have not been evaluated in advancement genioplasty procedures with large bone movements.

The aim of this study was to evaluate the stress distribution in titanium bicortical screws and pre-bent chin plates in simulated advancement genioplasty using finite element analysis (FEA).

Materials and Methods

Data acquisition and 3D model

A cone-beam computed tomography (CBCT) scan of a 26-year-old female patient which was obtained previously using Planmeca ProMax 3D (Planmeca, Roselle, IL, USA) was used to create a three-dimensional (3D) image of the mandibular bone. Images were saved in Digital Imaging and Communications in Medicine (DICOM) format. The DICOM data was imported to MIMICS software (Materialise, Leuven, Belgium), segmented by 222 to 3071 HU (Haunsfield unit) values, and 3D object data was created. This data was imported to reverse engineering software (Geomagic 11.0, Geomagic Company, Morrisville, NC, USA) to clean and repair the data and create a 3D surface model of the mandible. The surface model was imported to SolidWorks 2018 software (Dassault Systemes SolidWorks Corp., Waltham, MA, USA) to create a 3D solid model. Finite element models including the cortical and cancellous bones were employed and the mean cortical bone thickness was defined as 1.5 mm.

Surgical treatment simulation

A surgical treatment plan was simulated with an 8 mm advancement of the chin. The genioplasty technique simulated in the experiment was a horizontal osteotomy of the chin created approximately 5 mm below the inferior margins of the mental foramina and parallel to the horizontal plane. 2.0 mm titanium screws and 2.0 mm pre-bent titanium 4-hole chin plate with 8 mm step (KLS Martin, Tuttlingen, Germany) were measured using a digital caliper and the information obtained was used to create solid 3D models of hardware via SolidWorks software. Using the SolidWorks assembly module, all 3D models were assembled considering the surgical plan, and the assembly model was exported to STEP format. In the first model, two screws (2.0x19 mm) were placed bicortically (Figure 1A); in the second model, a centrally placed pre-bent chin plate was fixed with two screws (2.0x11 mm) in the chin and another two in the mandible (Figure 1B) virtually. The STEP data was imported to ANSYS 18.1 Workbench software to perform the finite element simulation.

Finite element model

In this finite element study, firstly the model was opened using ANSYS SpaceClaim module to repair the geometric faults (e.g., split edges, extra edges, and inexact edges) and prepared for analysis. Secondly, using ANSYS Mesh module, the 3D mesh model was generated. The locations where critical stresses will occur were subjected to a more stringent mesh process. In the mesh structure; the numbers of the elements and nodes were 165117 and 275006 respectively for the screw fixation model, and 182555 and 300082 for the plate fixation model (Figure 2). Mechanical properties of the materials were defined in the ANSYS Workbench. Poisson's ratio and modulus of elasticity of all materials were obtained from the literature (17) (Table 1). All materials were considered isotropic, homogenous, and linearly elastic. The finite element package of ANSYS Workbench software was used to establish boundary conditions and loading conditions for the components of solid models. The symmetric boundary condition was applied to the symmetric region and the fixed support boundary condition was applied to the posterior region (Figure 3). Two different loads representing the muscle forces that can affect the distal segment during the postoperative bone healing period in a clinical situation were applied to each model. A load of 15 N parallel to the mandibular occlusal plane was applied back-

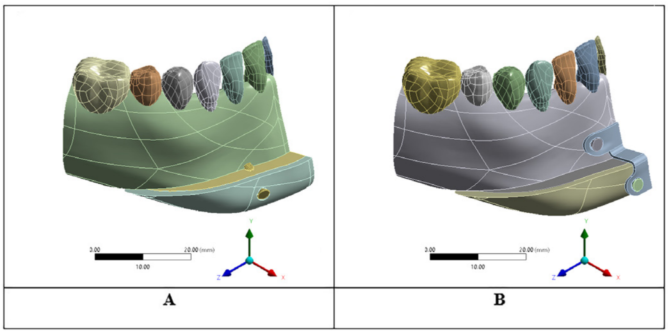

Figure 1. *Mandible models with simulated advancement genioplasty and fixation systems. (A) Screw fixation system; two screws (2.0x19 mm) were placed bicortically. (B) Plate fixation system; centrally placed pre-bent chin plate was fixed with four screws (2.0x11 mm).*

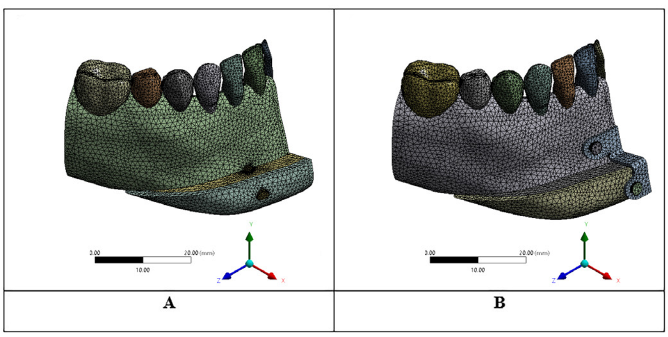

Figure 2. *Finite element mesh generation. (A) Screw fixation (B) Plate fixation.*

Table 1. *Mechanical properties of the materials.*

Structure	Modulus of elasticity (MPa)	Poisson's ratio
Cortical bone	13700	0,3
Medullary bone	1370	0,3
Titanium (Ti-6Al-4V)	110000	0,35

wards to the lingual surface of the chin segment, simulating the forces of the suprahyoid muscles. A load of 7 N perpendicular to the mandibular occlusal plane was applied upwards to the buccal surface of the chin segment, simulating the force of the mentalis muscle (Figure 3). The connections were contacted with frictionless contact and a non-linear solution was generated for each finite element model. The finite element solution took 8 iterations for the screw fixation model and 11 iterations for the plate fixation model (Figure 4).

The stress distribution and the deformation in the bone and fixation appliances were analyzed by the FEM. The distribution of stresses was analyzed with the equivalent von Mises stress criterion.

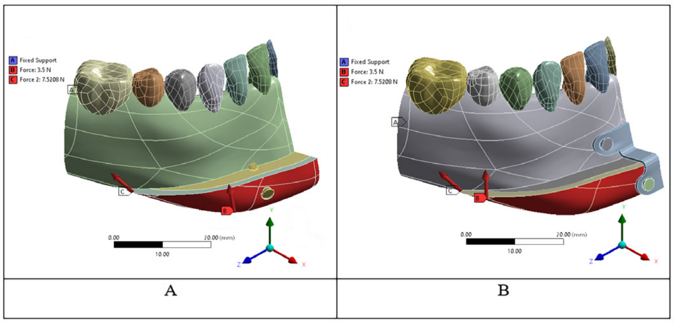

Figure 3. *Loading and boundary conditions in finite element simulations. (A) Screw fixation (B) Plate fixation.*

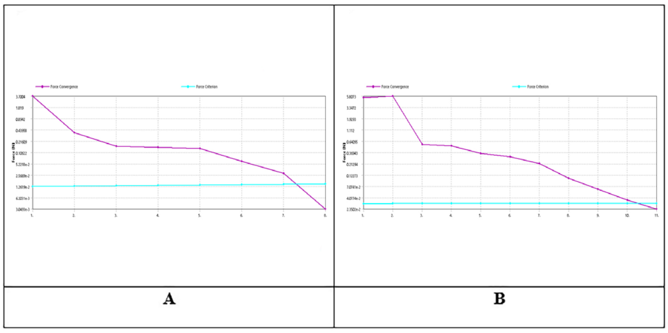

Figure 4. *Solution process and the total number of iterations. (A) Screw fixation (B) Plate fixation.*

Results

Higher stress values were observed for double screw fixation in comparison with a single chin plate fixation (Figure 5). For the screw fixation system, the maximum equivalent stress of 22.52 MPa was observed on the screw, and for the plate fixation system maximum equivalent stress of 13.71 MPa was observed on the plate (Figure 6) (Table 2).

Maximum equivalent stress values observed in the cortical bone of the proximal segment were 14.93 MPa in the screw

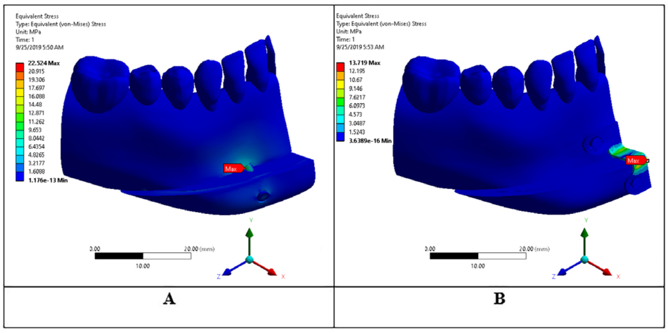

Figure 5. *Distribution of von Mises stresses in the structures. (A) Screw fixation (B) Plate fixation.*

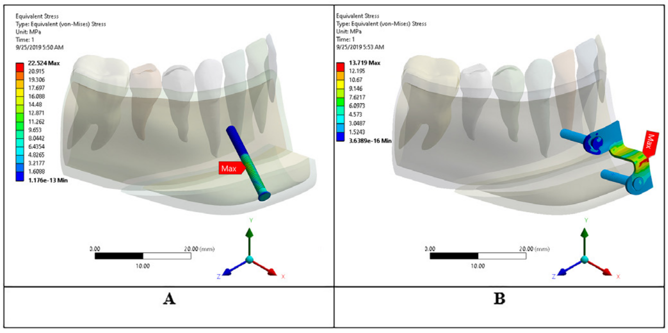

Figure 6. *Distribution of von Mises stresses in the fixation appliances. (A) Screw fixation (B) Plate fixation.*

Table 2. *Maximum equivalent (von Mises) stress values and deformation values.*

Fixation type	Maximum equivalent stress (MPa)	Deformation (mm)
Screw fixation	22.52	0.021
Plate fixation	13.71	0.0007

system and 2.74 MPa in the plate system (Figure 7). Maximum equivalent stress values observed in the cortical bone of the lower segment were 4.41 MPa in the screw system and 11.81 MPa in the plate system (Figure 8). In screw fixation system, the maximum stress (14.93 MPa) was observed in the part of the osteotomy line close to the screw body at the cortical bone of the proximal segment. In the plate fixation system, the maximum stress (11.81 MPa) was observed in the part of the osteotomy line under the plate at the cortical bone of the distal segment.

Maximum deformations were observed in the distal segments in both models. In the screw system, maximum deformation was 0.021 mm and observed in the chin region. In the plate system, maximum deformation was 0.0007 mm and observed in the posterior part of the distal segment (Figure 9) (Table 2).

Discussion

The long-term success of orthognathic surgery procedures resulting in ideal esthetic and function depends on skeletal and soft tissue stability that is obtained by achieving optimal osseous union. As with other maxillofacial osteotomies, two important mechanisms affect the stability of advancement genioplasty carried out by the osteotomy of the lower edge

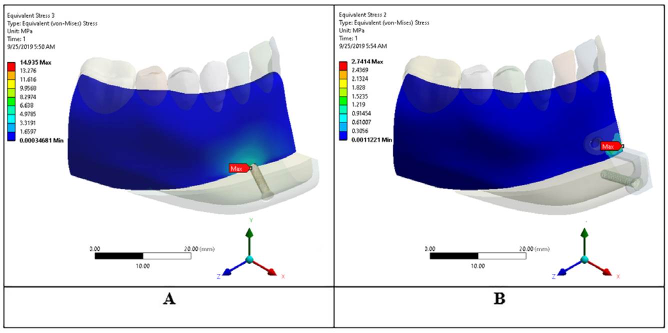

Figure 7. *Distribution of von Mises stresses in the cortical bone of the proximal segment. (A) Screw fixation (B) Plate fixation.*

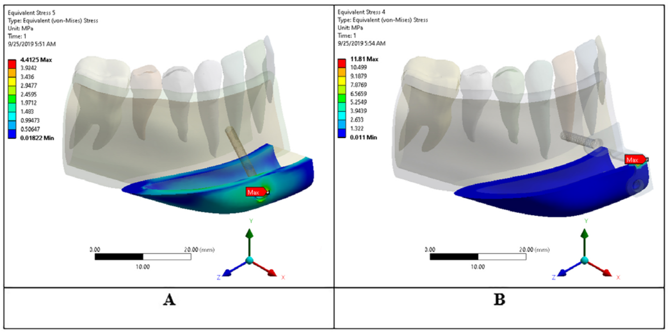

Figure 8. *Distribution of von Mises stresses in the cortical bone of the distal segment. (A) Screw fixation (B) Plate fixation.*

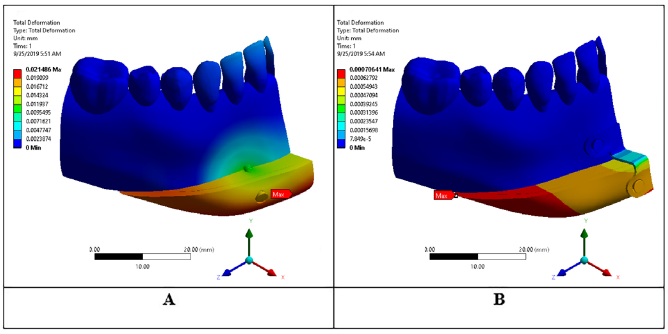

Figure 9. *Distribution of deformation in the structures. (A) Screw fixation (B) Plate fixation.*

of the mandible. The first one is the skeletal instability that may alter the surgical outcome by causing a change in the position of the genial segment before the osseous union. The second one is the osseous remodeling process, during which the advanced genial segment is slowly recontoured and may cause the final result to differ from the immediate postoperative outcome (1,7,18).

Fixation method, magnitude of surgical movement, and other factors such as age, gender, and occurrence of complications are possible factors that may influence the postoperative relapse rate in advancement genioplasty (2). Even though advancement genioplasty is considered a reliable surgical procedure with only minor relapses (2,8,10-12,19), the surgical results may not always be predictable, especially in large vertical and horizontal bony movements. The great propensity of the advanced genial segment to displace downward and posteriorly because of the tendency of the suprahyoid musculature and perimandibular connective tissues to retain the inferior segment in the original anatomic position contributes to potential bony instability and undesired resorption especially when semirigid fixation is used (1,3,12,14,20,21). Additionally, the genial region is also vulnerable to external forces in daily life and sleep. Immobility of the repositioned genial segment should be achieved with a proper fixation technique before osseous union, for predictable results (14).

The literature is replete with studies reporting the use of different fixation techniques in genioplasty but there is still controversy about which of these methods is more successful regarding the skeletal stability, clinical advantages, and long-term results. In some studies, the instability of the bony segment due to the fixation method was held responsible for recurrence (15,21), while others indicated that the amount of recurrence was not related to the fixation method (2,9-11,22,23). At this point, the distinction between short-term bone healing and long-term bone remodeling should be considered. The close approximation of the bony segments by providing maximum stability promotes early osteogenesis and enhances short-term bone healing.

Rigid internal fixation is usually performed with the aid of screws, miniplates, and pre-bent chin plates in genioplasty procedures (14,20,24). Osteosynthesis with bone plates and/or screws has certain technical advantages regarding skeletal stability, especially in cases with complex, asymmetrical, and large chin movements (6,11,12,18,21). Although 3D planning is very helpful in preoperative planning, still the final decision of whether to use plate and/or screw osteosynthesis is often made during surgery in the operating room.

Pre-bent chin plates have become increasingly popular due to their ease of manipulation, and fixation with a single chin plate placed to the midline in the symphysis is often preferred (2,14,20). Screw osteosynthesis is also a viable option in genioplasty procedures, but the applicability of the technique depends on the osteotomy type and the direction of movement of the genial segment and it may be technically more challenging and sensitive than plate osteosynthesis (20). For screw fixation alone, the 2.0 mm bicortical screws are usually employed and a minimum of two screws is needed to achieve initial segmental stability (20,24). After the down-fractured segment is mobilized, it is relatively difficult to prepare the screw holes and insert the screws with maintaining the intraoperative segmental stability. When placing bicortical screws, holding the distal segment may cause undesired displacement of the distal segment that directly affects the postoperative symmetry of the chin. It is not easy to notice an asymmetry at the time of surgery and it may be obvious days or weeks after the operation. When genioplasty is performed to achieve the retro positioning of the chin, fixation with screws is difficult or even impossible because stabilization can be only possible if the screw can reach the far cortex (6,20). In the fixation of multisegmental osteotomies, maintaining the planned positional relationship between the bone fragments seems to be technically more difficult during the insertion of bicortical screws compared to the plates.

The amount of surgical movement is another important factor that could affect the stability of the procedure. The more the chin is advanced, the less the soft tissue follows the advancement due to the more tension on the soft tissues and the muscles (2,12). However, the results of some studies evaluating the effect of the magnitude of genial advancement on relapse rates indicated no significant correlation between the amount of surgical movement and the amount of long-term relapse in the hard and soft tissues (3,8,10,19). Based on the knowledge that the main technical advantage of rigid fixation is successful applicability in large advancements and three-dimensional repositioning; in this study, the amount of chin advancement was determined as 8 mm, taking into account previous studies using 7 mm (3,8) or 8 mm (12,19) advancement, and the even-numbered step lengths of the pre-bent chin plates of the selected company.

In the present study, a FEA was used to compare the stability of fixation with pre-bent chin plate and screws. FEA is a numerical analysis method widely applied in engineering and is a powerful research tool that can be used to solve biomechanical problems in oral and maxillofacial sciences. Stress analysis obtained from finite element modeling of maxillofacial bony structures can provide information about the complex biomechanical behavior of bone and hardware affected by mechanical loading (25,26).

Although FEA is useful in the evaluation of osteotomy procedures, it has some limitations (27). Finite element modeling involves some assumptions and simplifications about material properties that differ from real clinical conditions. For example, bone is modeled as isotropic and homogeneous whereas, in fact, it is anisotropic and nonhomogeneous (26). In this study, it was assumed that the osteotomy line was smooth and clear and that the contacts between the bone and the osteosynthesis systems were 100%, but these conditions cannot be achieved in a clinical situation. In addition, in this study only the muscle forces acting on the distal segment were considered, however external forces that may affect this region during daily life and at sleep were not considered.

During the postoperative bone healing period, the distal segment is subjected to the retraction forces of the suprahyoid muscles, especially the anterior belly of the digastric muscle, which originates from the digastric fossa on the lingual surface of the mandible, and the geniohyoid muscle, which originates from the inferior mental spine of the symphysis menti. The mentalis muscle originates from the mental protuberance of the mandible near the midline and provides a weak upward-inward movement of the soft tissue complex of the chin. In this study, to represent the muscle forces to which the chin segment would be subjected in a clinical situation, a 15 N load parallel to the occlusal plane was applied backwards simulating the forces of the suprahyoid muscles and a 7 N load perpendicular to the occlusal plane was applied upwards simulating the force of the mentalis muscle. The backward applied loads were determined by considering the study by Ramos *et al.* (28).

There are many papers comparing titanium screw and plate osteosynthesis systems in terms of postoperative stability in other mandibular osteotomies. Although the results of these studies varied, generally it has been indicated that the factors that appear to have the greatest influence on the stability were the magnitude and direction of the bone movement. To the best of our knowledge, the only report that comparatively evaluated the stability of monocortical miniplate and bicortical screw systems in advancement genioplasty is the study by Aktı and Kalaycı (16) in which five different fixation models were evaluated in 5 mm advancement genioplasty using finite element analysis. They reported that better stability and less displacement were observed in the bicortical screw fixation groups, but the plate groups were more favorable in terms of tensile and compression stresses. The present study demonstrated that; plate osteosynthesis showed slightly better stress distribution and less deformation than screw osteosynthesis, and in both fixation systems the maximum stress values in the bone and titanium fixation appliances were far below the yield strength values described for bone and Ti-6Al-4V alloy in the literature (29). Further studies performing fatigue analysis by applying higher forces to the genial segment in advancement genioplasty can be undertaken.

The decision of the fixation method to be used depends on the clinical characteristics of the case, such as the magnitude and the direction of segmental movement or the number of bone segments. Surgeons should be able to make this decision intraoperatively based on the final position of the advanced genial segment and considering the stresses that may affect the postoperative results.

Conclusion

Fixation with a single centrally positioned titanium miniplate is slightly more stable than fixation with two bilaterally positioned titanium bicortical screws in advancement genioplasty. Both osteosynthesis systems can withstand the loads that are exerted by the muscles that attach to the chin in the postoperative remodeling period.

Türkçe özet: *İlerletme genioplastisinde vida ve plak osteosentezinin karşılaştirilmasi: sonlu elemanlar analizi çalışması. Amaç: Bu çalışmanın amacı, ilerletme genioplastisinde vida ve plak fiksasyon sistemlerindeki stres dağılımını sonlu elemanlar analizi ile değerlendirmektir. Gereç ve Yöntem: Bir hastaya ait konik ışınlı bilgisayarlı tomografi görüntüleri kullanılarak mandibular kemiğinin üç boyutlu sanal modelleri oluşturulmuştur. Bilgisayar destekli tasarım programında çene ucunun horizontal osteotomisini takiben 8 mm'lik çene ucu ilerletmesi simüle edilmiştir. Distal segment, ilk modelde bilateral olarak yerleştirilen iki adet titanyum mini vida ile ve ikinci modelde ortaya yerleştirilen tek bir 4 delikli titanyum önceden bükülmüş genioplasti plağı ile stabilize edilmiştir. Plak, iki adet proksimal ve iki adet distal segmentte olmak üzere toplam dört adet mini vida ile fikse edilmiştir. Tüm fiksasyon araçları, çene ucunun lingual yüzeyine oklüzal düzleme paralel olarak lingual yönde uygulanan 15 N'luk ve çene ucunun bukkal yüzeyine oklüzal düzleme dik olarak yukarı yönde uygulanan 7 N'luk kuvvetlere maruz bırakılmıştır. Kemik ve titanyum materyallerdeki von Mises stres dağılımları ve deformasyonlar değerlendirilmiştir. Bulgular: Vida fiksasyon sisteminde (22,52 MPa), plak fiksasyon sistemine (13,71 MPa) göre daha yüksek stres değerleri gözlenmiştir. Deformasyon değeri vida fiksasyon sisteminde (0,021 mm), plak fiksasyon sistemine (0,0007 mm) göre daha yüksek bulunmuştur. Sonuç: İlerletme genioplastisinde, ortaya yerleştirilen tek bir önceden bükülmüş genioplasti plağı ile fiksasyon, bilateral yerleştirilen iki adet bikortikal vida ile fiksasyona göre daha iyi stabilizasyon göstermiştir. Her iki sistemdeki stres değerleri, kemik ve titanyumun fiziksel dayanım sınırları içerisinde kalmıştır. Anahtar kelimeler: Genioplasti, Plak, Vida, Sonlu elemanlar analizi, stres dağılımı*

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Peer-review: Externally peer-reviewed.

Author contributions: SG, SM, SH, ING, SU participated in designing the study. SG, SM, SH, ING, SU participated in generating the data for the study. SG, SM, SH participated in gathering the data for the study. SG, SM, SH, ING, SU participated in the analysis of the data. SG, SH wrote the majority of the original draft of the paper. SG, SM, SH, ING, SU participated in writing the paper. SG, SM, SH, ING, SU has had access to all of the raw data of the study. SG, SU has reviewed the pertinent raw data on which the results and conclusions of this study are based. SG, SM, SH, ING, SU have approved the final version of this paper. SG guarantees that all individuals who meet the Journal's authorship criteria are included as authors of this paper.

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