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Comparison of the Effects of Different Fixation Methods on Fragments and Temporomandibular Joint in Sagittal Split Ramus Osteotomy Applied to Patients with Mandibular Asymmetry Using Three-Dimensional Finite Element Analysis

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Abstract

BACKGROUND/AIMS: Fixation of the mobilized bone fragments is of importance for the healing of the patients and stabilization of the osteotomy in the postoperative period. In our study, models with different degrees of asymmetry were fixed with different fixation methods and the results were evaluated.

MATERIALS AND METHODS: Models with right rotations of 2, 5, and 10 mm were fixed with three bicortical screws and two miniplates with four monocortical screws, and the results were compared with those of finite element analysis (FEA). Tension and compression stresses in the bone segments and temporomandibular joint of two different fixation methods were compared.

RESULTS: FEA showed that the tensile and compressive stresses in the buccal, lingual, and temporomandibular discs were higher with bicortical screws.

CONCLUSION: It was predicted that stabilization problems would increase with increasing motion in sagittal split osteotomy. When selecting the most stable fixation method, the least stress to the surrounding tissues should be taken into consideration.

Keywords: Three-dimensional finite element analysis, fixation systems, orthognathic surgery, sagittal split ramus osteotomy

INTRODUCTION

Mandibular osteotomies are surgical procedures performed on the ramus, corpus, and symphysis to treat mandible anomalies. Split osteotomy, which consists of osteotomies that separate the medial and lateral cortices of the ramus in the mandible.[1] Sagittal split ramus osteotomy (SSRO) was first described by Trauner and Obwegeser[2]. Dalpont modified the technique in 1961 by positioning the buccal osteotomy behind the 2nd molars to increase the contact between the bone segments. In 1968, Hunsuck described the osteotomy procedure that is commonly used today, which involves terminating the lingual osteotomy just behind the lingula, extending to the posterior border of the ramus.[1,2]

In SSRO, the mandible is segmented into two independent fragments, the proximal fragment and the distal fragment. In this technique, the distal bone fragment, which becomes free, is moved in a 3-dimensional plane. With a pre-prepared guide plate (occlusal splint) placed on the

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maxilla, the mandible is positioned in the required position and fixed with an appropriate fixation method.[3,4] Osteosynthesis methods in rigid internal fixation used in maxillofacial surgery consist of titanium mini-plates and monocortical and bicortical screws.[5]

The most important factors affecting the success of SSRO are stabilization, fixation instruments, and passive fusion of the bone fragments. As the movement speed increases, the changes in neighboring tissues and the stress on the tissues and fixation instruments also increase. Increased stress can also lead to changes in the sizes of miniplates, screws, and tissues.

Patients with mandibular asymmetry are treated with SSRO by changing the facial view, occlusion, and masticatory mechanics. With changes in the position of the mandible, the temporomandibular joint disk changes over time. The fixation methods used in osteotomy of the mandible lead to stress in the mandibular fragments and the temporomandibular joint. The stress on the mandible and temporomandibular joint increases with an increase in the amount of movement, which may lead to postoperative relapse, resorption, and temporomandibular joint disorders. The lack of a definite consensus on fixation methods directs surgeons to perform fixation based on observation and experience during the operation.[6]

Three-dimensional finite element analysis (FEA) and two-point biomechanical testing are the most important *in vitro* study designs developed to examine the reliability and effectiveness of fixation techniques. The FEA technique is a research method that can simulate the complex biomechanical analysis of the mandible close to reality and can change the direction and intensity of the forces applied on the model.[7] In studies conducted with three-dimensional FEA, both time and cost savings are achieved, and the results obtained in simulations are reported to be compatible with clinical studies.[8]

In this study, models with different degrees of asymmetry will be fixed with different fixation methods using the Hunsuck method with SSRO and right rotation of the mandible model. The results will be evaluated by performing static linear analysis with the three-dimensional finite element method on models with 2 mm, 5 mm, and 10 mm right rotation in three different cases. This study aimed to compare the stress caused by different fixation methods on the bone segments and temporomandibular joint in different magnitudes of rotation movements compared with the FEA method.

MATERIALS AND METHODS

This study was conducted at the Ankara University. The Declaration of Helsinki was complied with, and approval was obtained from Ankara University Faculty of Dentistry Ethics Committee (approval number: 36290600/42/2023, date: 19.06.2023). This study was designed in the format of FEA, and the materials used in the study were provided through the Human Visible Project. No volunteer data were used, and no consent form was required.[9]

In this study, six three-dimensional models with SSRO were fixed with two bilateral, four-monocortical screws and flat miniplates and three bicortical screws after 2 mm, 5 mm and 10 mm rotation movements. The effects on the buccal and lingual segments and the temporomandibular joint were then examined using three-dimensional modeling and FEA.

In this study, the tensile and compression forces on various regions of the mandible caused by the plate and screw systems applied for fixation were evaluated. The analysis focuses solely on the forces and changes resulting from the plates and screws without any external forces being applied to the mandible.

The tomography images needed to create the three-dimensional models in the study were obtained from the Human Visible Project conducted by the US National Library of Medicine.[9] The tomography images obtained from the Visible Human Project were scanned with a cross-sectional interval of 1 mm, and the ".stl" files of the three-dimensional toothed mandible model were transferred to 3D-Doctor (Able Software Corp., MA, USA) software in DICOM 3.0 format.[9] After simplification and reformatting processes were applied to the images with 3D-Doctor software, the images were transferred to Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103 USA) 3D modeling software for 3D modeling. In the Rhinoceros program, osteotomies in accordance with the Hunsuck technique were simulated on the mandible model and 2 mm, 5 mm and 10 mm rotation movements were made to the distal segment. After creating the models of the plates and screws, the models were placed in the correct coordinates in three-dimensional space, and the modeling process was completed. The models created using Rhinoceros software were converted into geometric models, and a mesh structure was created using VR Mesh Studio (Virtual Grid Inc. Bellevue City, WA, USA) software to prepare them for analysis. Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103 USA) 3D modeling software, VRMesh Studio (VirtualGrid Inc, Bellevue city, WA, USA), and Algor Fempro (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA 15238-2932 USA) analysis software was used for editing and homogenizing the 3D mesh structure, creating the 3D solid model, and finite element stress analysis.

The physical properties of the modeled cortical bone (Erkmen et al.[14]), spongiose bone (Erkmen et al.[14]), tooth (Ammoury et al.[15]), Ti-6 Al-4V (Bataineh and Janaideh[16], Shu et al.[18]), zygomatic process (Mirow et al.[17]), articular cartilage (Mirow et al.[17]), temporomandibular ligament (Li et al.[19]), and disc (Li et al.[19]) are shown in Table 1.

Statistical Analysis

Evaluation of Finite Element Stress Analysis Results

Since the values obtained as a result of finite element stress analysis are the result of mathematical calculations without variance, statistical

Table 1. Physical properties of the materials

	Young module (Mega Pascal)	Poisson ratio	References
Cortical bone	13,700	0.3	Erkmen et al.[14]
Spongious bone	1,370	0.3	Erkmen et al.[14]
Tooth	20,000	0.3	Ammoury et al.[15]
Ti-6 Al-4V	116,000	0.34	Bataineh and Janaideh[16]
Zygomatic bone	1,000	0.3	Mirow et al.[17]
Articular cartilage	0.79	0.49	Shu et al.[18]
	Matrix material constant	**Compression module**	
Temporomandibular ligament	6	0	Li et al.[19]
Disc	0.770562	1.41	Li et al.[19]

analysis cannot be performed. The precise evaluation and interpretation of the amount and distribution of stress in cross-sectional images and nodes is important.

In the analysis results, positive and negative values indicate tensile and compressive stresses, respectively. If the absolute value of a stress type is greater for a stress element, the stress element is under the influence of that stress type and should be evaluated.

The models with fixation with three linearly placed bicortical screws and two double-sided mini-plates with four monocortical screws and flat features are shown in Figure 1.

RESULTS

The maximum principal stress (tensile) values in the cortical bone are shown in the images on a scale ranging from red to blue, and the minimum principal stress (compression) values in the cortical bone are shown on a scale ranging from blue to red, as they are negative values.

The tensile and compressive stresses in the bone, which were rotated 10 mm to the right and fixed with two mini plates with bilateral, four-hole, and flat features, are shown in Figure 2, Graph 1, Table 2.

The tensile and compressive stresses in the bone, which were rotated 10 mm to the right and fixed with bicortical screws, are shown in Figure 3, Graph 2, Table 3.

DISCUSSION

SSRO is a popular osteotomy method for the correction of maxillofacial deformities and esthetic and functional incompatibilities of the mandible and maxilla. Fixation is important for the success of osteotomy to ensure the stabilization of bone fragments and healing.

Figure 1. Models fixed with 3 linearly placed bicortical screws and 2 mini plates with 4 monocortical screws.

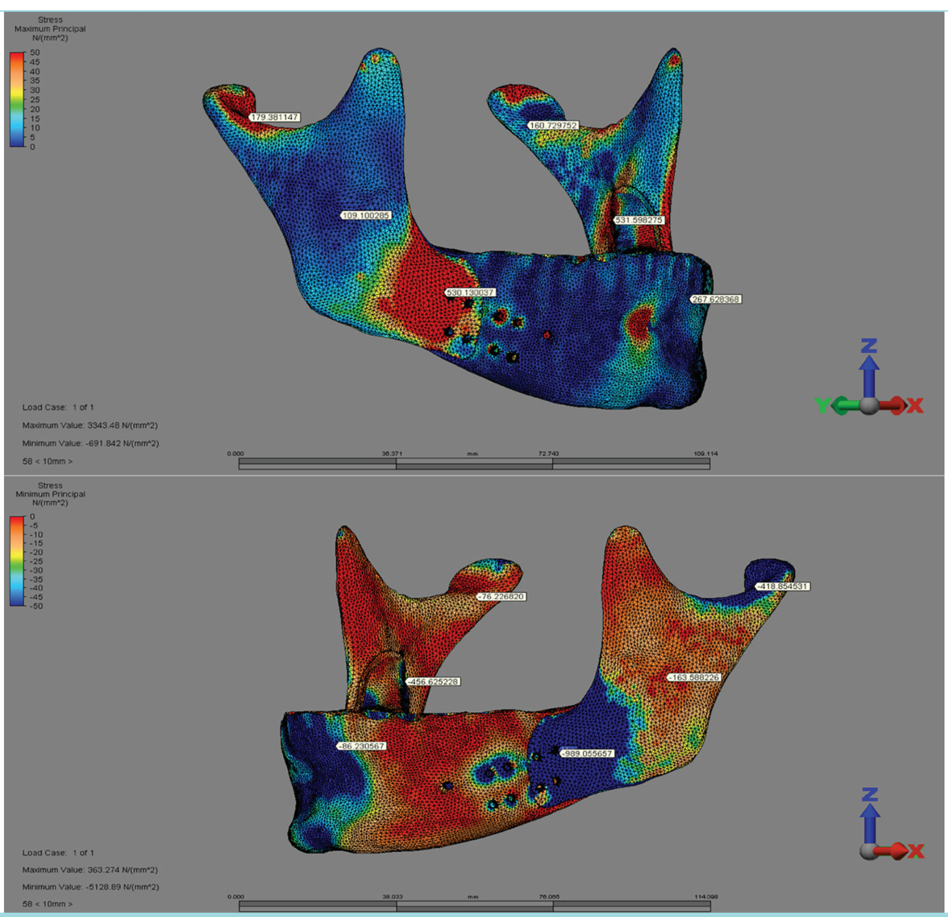
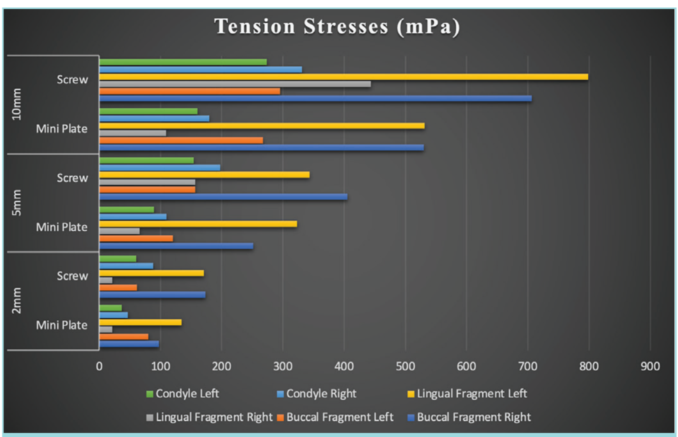


Figure 2. Stresses in bone rotated 10 mm to the right and fixed with 2 mini plates with 4 holes; (a) tension (b) compression.

The ideal fixation should provide the highest stability between the bone fragments, provide adequate resistance to displacement forces at the osteotomy site, and place less stress on the surrounding tissues to ensure proper healing.[6] As a result of the studies, the rigid internal fixation method has become the standard method, thus enabling patients to regain their postoperative functions more easily, and stabilization and relapse problems have been greatly reduced. In the rigid internal fixation class, postoperative complications are minimized using bicortical screws, monocortical screws, or combinations of the two, and fragment stabilization can be achieved.[10,11] Miloro[13] demonstrated in their study that the use of three bicortical screws for the fixation of SSRO was stable, with an average relapse rate of 0-8%. Sigua-Rodriguez et al.[11] reported that when two separate mini-plates are positioned in the tension and compression areas during fixation, the system is sufficiently resistant to displacement, resulting in lower stress at the osteotomy sites. In our study, we aimed to comparatively evaluate the fixation methods of three bicortical screws, which are considered more stable in the literature, and two mini-plates, which have been shown to generate less stress, using FEA.[11-13] Although rigid fixation with mini-plates and lag screws has several advantages, disadvantages such as nerve damage due to compression and displacement of the condyle from the fossa have also been reported.[6] In order to avoid these disadvantages of rigid fixation, there are also studies that mention semi-rigid fixation.[12] Mavili et al.[12] investigated the short- and long-term stability of their semi-rigid fixation method in 23 patients who underwent maxillofacial surgery and 12 patients who underwent mandibular regression surgery. It was reported that the semi-rigid fixation method consisting of two bicortical screws with a diameter of 2 mm for mandibular fixation provided adequate stability and no recurrence in the short- and long-term. While fixation was achieved with bicortical screws, care was taken to maintain the gap between the fragments to avoid loading on the temporomandibular joint, and bone grafts were used when necessary. To stabilize semi-rigid fixation, jaw movements of the patients were restricted with maxillomandibular elastics for 2-4 weeks after 48 hours postoperatively. In our study, three bicortical screws and two miniplates, which are rigid fixation methods, were compared. The graft model was not placed in the opening between the fragments as the mandible moved. The fragments could approach each other under the forces applied by the screws. It was observed that as the amount of movement of the mandible increased, the gap between the fragments also increased. It was observed that the bicortical screws, while providing rigid fixation on the one hand, tended to close the gap between the buccal and lingual segments more with the compression force applied, thus creating more stress.



Graph 1. Tensile stresses applied by bicortical screws and mini plates on fragments and condyle at different amounts of motion (Mega Pascal).

SSRO is a frequently preferred osteotomy method for the correction of maxillofacial deformities and esthetic and functional incompatibilities of the mandible and maxilla. Fixation is important for the success of osteotomy to ensure the stabilization of bone fragments and healing. The ideal fixation should provide the highest stability between the bone fragments, provide adequate resistance to displacement forces at the osteotomy site, and place less stress on the surrounding tissues to ensure proper healing.[6] In our study, the stress and compression values of bicortical screws were higher than those of miniplate fixation models. In cases in which the bone fragments are flimsy and thin, it may be recommended to prefer plates because unwanted fractures may occur during surgery with the stress caused by bicortical screws. In the long term, resorption and temporomandibular joint problems are more likely to occur in patients who are fixed with bicortical screws than with miniplate. Sato et al.[6] used five different rigid fixation techniques with miniplate and bicortical screws in a clinical setting. They fixed bone segments using rigid fixation methods in models that were advanced 5 mm with sagittal split osteotomy. They compared the stabilization values obtained by applying a force on the first molar tooth and evaluated these results using FEA. They reported that FEA is a numerical method for evaluating biomechanical problems and a powerful research tool that can provide precise information about the stress behavior of the mandible affected by mechanical forces. They reported that the mechanical connections between the distal and proximal segments, fixation materials, and stress in adjacent areas can be measured using this method. In the study, it was reported that the bicortical screw had higher stability than the mini plate. They explained that bicortical screws provide better three-dimensional stabilization than mini-plates because they attach to both bone segments. The mini-plates provide stabilization with a structure of bridge between the screws that provides force transmission, thus allowing flexion against external torsional forces. A force fracture transmits a lower compressive force to

Table 2. Tensile stresses applied by bicortical screws and mini plates on fragments and condyle at different amounts of motion (Mega Pascal)

		2 mm		5 mm		10 mm	
		Mini plate	Screw	Mini plate	Screw	Mini plate	Screw
Buccal fragment	Right	97,622	173,353	251,317	405,024	530.13	706,419
	Left	80,074	61,609	120,317	156,881	267,628	294,963
Lingual fragment	Right	21,325	21,241	65,784	156,699	109.1	443,458
	Left	134,445	170,955	322,753	343,631	531,598	798,638
Condyle	Right	46,901	88,231	109,482	197,787	179,381	330,987
	Left	36,792	60,602	89.49	154,062	160,729	273,456

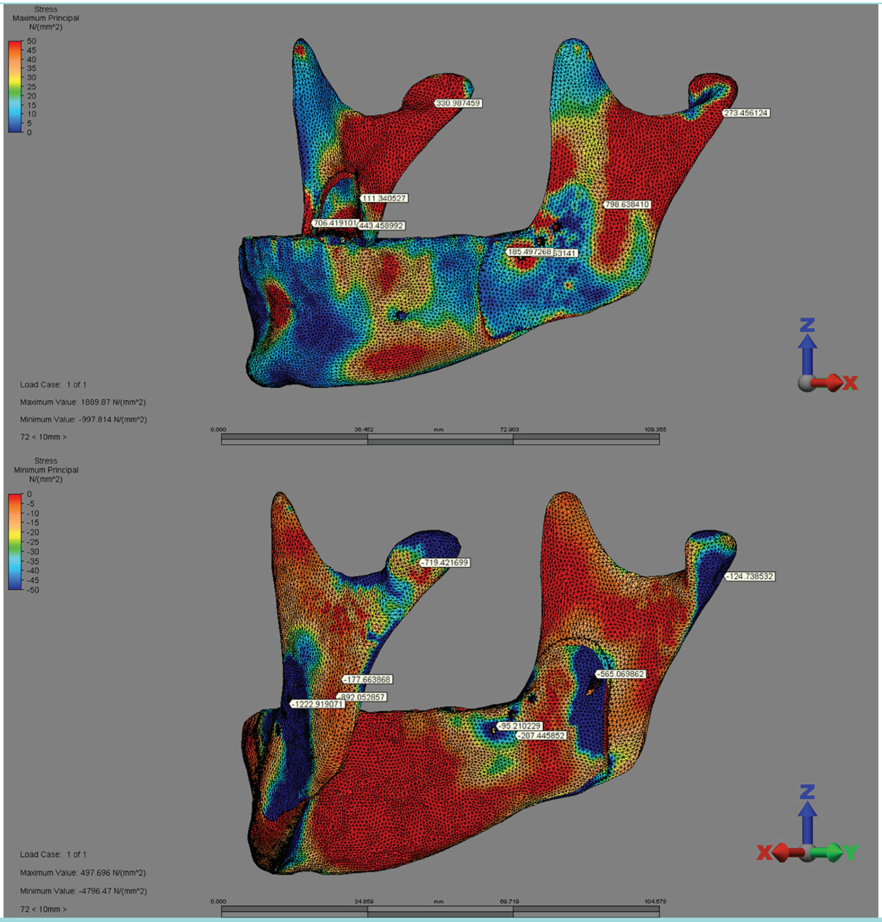
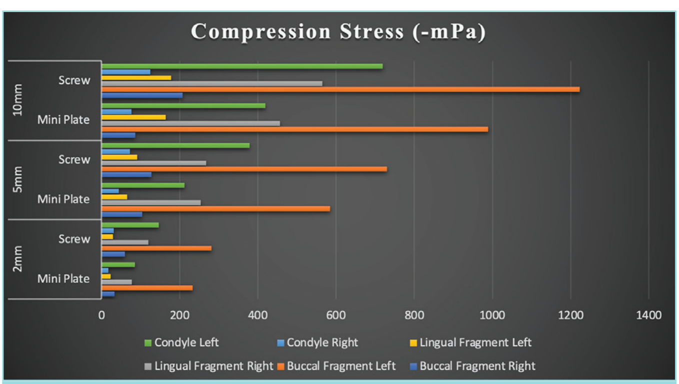


Figure 3. Stresses in bone rotated 10 mm to the right and fixed with 3 bicortical screws; (a) tension (b) compression.



Graph 2. Compressive stresses applied by bicortical screws and mini plates on fragments and condyle at different amounts of motion (Mega Pascal).

the bone fragments and lower torque force to the temporomandibular joint. Therefore, mini-plates have been reported as an alternative to bicortical screws in terms of biomechanical strength and transmitted stresses in sagittal split osteotomies. In the present study, we aimed to evaluate the stresses that may occur between segments using different fixation methods using FEA. It was found that the compression and tensile forces in the models fixed with the miniplate used were lower than bicortical screws. This may be explained by the fact that the force-transmitting plate allows flexion and force fracture. The stresses caused by the transmission of lower torque force to the temporomandibular joint were also lower in models with mini-plate fixation. Our results support the view that mini-plates are a good alternative to bicortical screws because of their lower stress generation.

FEA is a powerful in vitro method that can provide highly accurate information regarding the biomechanical behavior of the mandible, which exhibits diverse and complex properties. This method allows for the definition of different material characteristics and the modification of the magnitude and direction of the applied forces in the designed models. Three-dimensional FEA reflects the stress behavior on the models in a manner that is closer to reality than other in vitro methods, taking into account the complexities of clinical conditions.[20] The objective of studies conducted using the FEA method is to predict the behavior of designed biomaterials and existing systems, thereby guiding surgeons' clinical decisions in a more predictable manner. In this study, we chose to employ this method for the aforementioned reasons.

Study Limitations

There are some limitations to this study, including the FEA. Although the mandibular bone model created by three-dimensional FEA is defined as isotropic, homogeneous, and linear elastic, the mandible is anisotropic and heterogeneous. Anatomically, each mandible has a different cortical bone density, spongiosis bone density, and masticatory-occlusive mechanics. The deformation characteristics and resorption patterns of each patient's mandible differ according to external effects.

Table 3. Compressive stresses applied by bicortical screws and mini plates on fragments and condyle at different amounts of motion (Mega Pascal)

		2 mm		5 mm		10 mm	
		Mini plate	Screw	Mini plate	Screw	Mini plate	Screw
Buccal fragment	Right	-33,341	-59,195	-103,833	-127.6	-86.23	-207,445
	Left	-233,365	-280,726	-584.12	-730,419	-989,055	-1222.919
Lingual fragment	Right	-77,269	-119,708	-253.33	-267,014	-456,625	-565,069
	Left	-22,858	-29,251	-65,483	-91,513	-163,588	-177,663
Condyle	Right	-17,531	-31,503	-43,639	-72,204	-76,226	-124,738
	Left	-84,762	-146,74	-212,205	-378,342	-418,854	-719,421

A standardized and homogeneous mandible can be projected by FEA. In spite of these disadvantages, it is often preferred in scientific research due to its advantages, such as imitating biomechanically complex structures as close as possible to reality, changing the intensity and direction of the forces to be applied, and defining different material properties. The results obtained in this study need to be supported by clinical studies.

CONCLUSION

After sagittal split osteotomy, the mandibular models were rotated 2 mm, 5 mm, and 10 mm to the right and fixed using two different methods: three bicortical screws in a linear position and two mini plates with four screws. After fixation, the tension and compression stresses on the buccal and lingual bone segments on the right and left sides of the mandible and condyle were analyzed. The stress on the condyle and bone fragments increased as the movement speed increased. When we compared the two different fixation techniques, the stresses on the bone segments and condyle were higher in fixation with bicortical screws.

It was predicted that stabilization issues would increase with increasing the amount of motion during sagittal split osteotomy. When selecting the most stable fixation method, the least stress to the surrounding tissues should be taken into consideration.

MAIN POINTS

- Stabilization of the fixation is an important factor affecting the success of sagittal split osteotomy.
- Bicortical screws, monocortical screws, and plates are commonly used for rigid internal fixation.
- Bicortical screws used during fixation may cause higher tensile and compressive stresses than monocortical screws and plates.

ETHICS

Ethics Committee Approval: The Declaration of Helsinki was complied with, and approval was obtained from Ankara University Faculty of Dentistry Ethics Committee (approval number: 36290600/42/2023, date: 19.06.2023).

Informed Consent: Not applicable.

FOOTNOTES

Authorship Contributions

Surgical and Medical Practices: M.Ö., Concept: M.Ö., S.A., Design: M.Ö., S.A., Data Collection and/or Processing: M.Ö., S.Ö.K., Analysis and/or Interpretation: M.Ö., Literature Search: M.Ö., S.Ö.K., Writing: M.Ö., S.Ö.K.

Conflict of Interest: No conflict of interest was declared by the authors.

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