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Comparison of Stress Values in Reconstruction Plate-Screw System in Different Lengths of Lateral Mandibular Defects by Finite Element Analysis: Methodological Study

Farklı Uzunluklardaki Lateral Mandibular Defektlerde Kullanılan Rekonstrüksiyon Plak-Vida Sisteminde Stres Değerlerinin Sonlu Element Analizi ile Karşılaştırılması: Metodolojik Çalışma

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ABSTRACT Objective: This study examines the effect of locking plates on fixation reliability in mandibular lateral defects of different lengths through finite element analysis. **Material and Methods:** A 3D model of the mandible of a 40-year-old male patient was obtained using computerized tomography. In the 3D model, 2 segmental resections measuring 25 and 50 mm in length were performed on the left mandible corpus region. The following were examined: stress values, distribution and concentration regions at the reference points on the cortical and cancellous bones, and the screw-plate system depending on the length of the locking reconstruction plates. **Results:** The present results showed that with increasing resection length, the tensile forces (maximum principal stress) decreased in the proximal segment, except for the screw furthest from the resection area, whereas no significant change was observed in the distal segment. As regards the compression forces (minimum principal stress), no significant change was observed in the distal segment, whereas an increase was observed in the bone around the screws furthest from the resection area in the proximal segment. **Conclusion:** The results suggested that as defect length increases, the middle region of the plate should be thicker.

Keywords: Finite element analysis; mandibular reconstruction

ÖZET Amaç: Bu çalışma, farklı uzunluklardaki mandibular lateral defektlerde kilitli plakların fiksasyon güvenilirliğine etkisini sonlu elemanlar analizi ile incelemektedir. **Gereç ve Yöntemler:** Bilgisayarlı tomografi kullanılarak 40 yaşındaki erkek hastanın mandibulasının 3 boyutlu modeli elde edildi. 3D modelde sol mandibula korpus bölgesinde 25 ve 50 mm uzunluğunda 2 segmental rezeksiyon yapıldı. Kortikal ve spongioz kemikler üzerindeki referans noktalarında stres değerleri, dağılım ve konsantrasyon bölgeleri ve kilitli rekonstrüksiyon plaklarının uzunluğuna bağlı olarak vida-plak sistemi incelendi. **Bulgular:** Rezeksiyon uzunluğu arttıkça proksimal segmentte çekme kuvvetlerinin (maksimum asal stres) rezeksiyon alanından en uzaktaki vida dışında azaldığını, distal segmentte ise anlamlı bir değişiklik gözlenmediğini gösterdi. Kompresyon kuvvetleri (minimum asal stres) ile ilgili olarak distal segmentte önemli bir değişiklik gözlenmezken, proksimal segmentte rezeksiyon alanından en uzak vidaların etrafındaki kemikte bir artış gözlendi. **Sonuç:** Sonuçlar defekt uzunluğu arttıkça plak orta bölgesinin daha kalın olması gerektiğini düşündürdü.

Anahtar Kelimeler: Sonlu element analizi; mandibular rekonstrüksiyon

Segmental mandibular resection techniques are commonly used for tumor or cyst resection procedures. Following segmental resection, reconstruction plates should be used for initial position of the segments, to maintain spaces, and to stabilize the mandible. A reconstruction plate that bridges defects is used to decrease the tumor recurrency within the first year post operation. When a patient has a poor general health due to end-stage cancer, reconstruction plates may be used during the first surgical op-

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eration. Studies, however, have reported that reconstruction procedures has more success in the second surgery than in the initial surgery.[1]

Reconstruction plates may have some disadvantages, such as fracture of the plate and screws, plate exposure, loose of the screws, infection, formation of fistula, and limited function and aesthetic.[2,3] For the management of these complications, various reconstruction plate configurations have been used, such as locking or non-locking systems.

Locking systems display some superiority over non-locking systems. Researches have reported that locking systems are advantageous in terms of screw loosening, plate adaptation, segment positioning and occlusal relationship, primer stability and cortical blood supply.[1] However, studies on non-locking or locking systems' stability remain limited.[2-5]

The aim of teh study is examine the effect of using locking plates on fixation reliability in mandibular lateral defects of different lengths through finite element analysis (FEA).

MATERIAL AND METHODS

This study was approved by Başkent University Institutional Review and was financially supported by Başkent University Research Fund. This study was conducted in accordance with the Principles of the Declaration of Helsinki.

Computerized tomography were used to obtain a 3D model of the mandible of a 40-year-old male patient. In the 3D model, 2 segmental resections measuring 25 and 50 mm in length were performed on the left mandible corpus region. The following were examined: stress values, distribution and concentration regions at the reference points on the cortical and cancellous bones, and the screw-plate system depending on the lengths of the locking reconstruction plates. Static linear analysis and three-dimensional finite element stress analysis were performed. Models that were mathematically divided into a finite number of elements and organized into a matrix were solved with the help of a computer.

The construction of a more homogeneous 3D network structure, the creation of a solid 3D model, and the finite element stress analysis were performed using the following: a computer with Intel Xeon® R CPU 3.30 GHz processor (Intel, California,USA), 500 GB hard disk, 14 GB RAM and a Windows 7 Ultimate Version Service Pack 1 operating system; an Activity 880 (Smart Optics Sensortechnik GmbH, Sinterstrasse 8, D-44795 Bochum, Germany) optical scanner for 3D scanning; and Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103 USA) 3D modeling software and Algor Fempro (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA 15238—2932 USA) analysis program.

Models were created geometrically with the VRMesh software (VRMesh, USA) and they were transferred to the Algor Fempro (Algor Inc., USA) software in stl format. Stl format is universally used in 3D modeling programs. Given the coordinate information of the nodes are stored in the stl format, no information was lost when transferred between programs. It was necessary to introduce model to the software that analysed the mandible and the material from which the tooth structures are made.

Material values (poisson ratio and elasticity modulus) that describe physical properties were assigned to the structures (Table 1). Mechanical properties of the materials were obtained from literature.[6,7]

Locking reconstruction plates and screws were scanned at the macro scale in 3D by a SmartOptics 3D (Smart Optics Sensortechnik GmbH, Bochum, Germany) scanner. The models obtained in the stl format were sent to the VRMesh 3D mesh editing software. The parts corrected in the process in the process sent to Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103 USA) software. In the Rhinoceros software, confirmation between implants, plates, screws and bone tissues, as well as force transfer, was achieved by the Boolean method.

TABLE 1: The material values.

	Young's modulus (MPa)	Poisson ratio
Spongious bone	1500	0.3
Cortical bone	15000	0.3
Titanium	110000	0.33
Cr-co	134000	0.33
Porcelain	82800	0.35

Lateral jaw defect models have the following characteristics: For the 25 mm model: fixed with a 2.4 system, made from titanium, with nine holes, 72 mm long, 2.5 mm thick, 8 mm wide, and 8 mm hole gap. For the 50 mm model: fixed with a 2.4 system, made from titanium, with 12 holes, 90 mm long, 2.5 mm thick, 8 mm wide, 8 mm hole gap reconstruction plates, and 13 mm long screws with an outer diameter of 2.4 mm, an inner diameter of 1.7 mm, a screw pitch of 1 mm, and a head diameter of 4 mm.

For bone tissue modelling, tomography was taken first using a 3M Iluma CBCT device (HYTEC Technology Center, 110 Eastgate Drive, Los Alamos, New Mexico 87544, USA) at 120 KvP, 3.8 mA and 40 s scan mode.

The radiographs were transferred to 3D-Doctor software (3D-DOCTOR, USA), and bone tissue was separated based on the Hounsfield values through interactive segmentation. After process of separation, a 3D model was obtained using the 3D rendering method, and the bone tissue was modelled as above. Cancellous bone was obtained from bone tissue by the offset method.

Teeth in cortical bone were deleted in VRMesh software. Bone cuts were made in desired sizes. Screws were placed and bone cuts were made to ensure the force transmission between screws and bone tissues.

In this way, the mandible, cancellous bone, cortical bone, plates, screws, the implant that provides the connection with the upper jaw (used for fixation), the implant superstructure and the crown parts have been transferred to the model in a way that reflects its true morphology. The models are placed in the correct coordinates in 3D space in Rhinoceros software. Fixation of the reconstruction plates in the models was simulated with 3 screws, as stated in the literature.[8,9] The models made in Rhinoceros have been transferred to Fempro software by preserving 3 dimensional coordinates.

Mathematical model consists of 210604 nodes and 939056 elements for the locking plate model in short lateral defect and 228295 nodes and 1017364 elements in long lateral defect.

The model is fixed in condyle area and upper surface of crown with zero movement at each degree of freedom. It is assumed that there will be no friction by fixing the screw and plate to each other exactly in the locked system.

Minimum (maximum compression) and maximum (maximum tension) principal stresses values for the cortical bone were obtained according to highest value 1 mm far away from screws in cortical bone.

Von Mises stress distributions of screws and plates, and minimum (maximum compression) and maximum (maximum tension) principal stresses values for cortical bone were evaluated in non-locking plate/screws model and locking plate/screws model.

RESULTS

Principle stress max (tensile) was found to be 4.10 MPa and principle stress min (compression) was found to be -1.85 MPa in proximal cortical bone in 25 mm length resected and using locking screws models, under appropriate loading condition (Table 2) (Figure 1, Figure 2, Figure 3).

Principle stress max (tensile) was found to be 3.55 MPa and principle stress min (compression) was found to be -4.66 MPa in proximal cortical bone in 50 mm length resected and using locking screws models,

TABLE 2: Principle stress max and principle stress min in proximal cortical bone in 25 mm length resected and using locking screw models.

	Distal			Proximal		
Screws	**3**	**2**	**1**	**1**	**2**	**3**
Principle stress max	0.35	1.21	0.28	3.50	4.10	3.41
	0.82	0.41	0.14	3.64	2.53	1.09
Principle stress min	-0.29	-0.29	-0.03	-0.49	-1.85	-1.60
	-0.39	-0.37	-0.13	-0.96	-1.43	-1.71

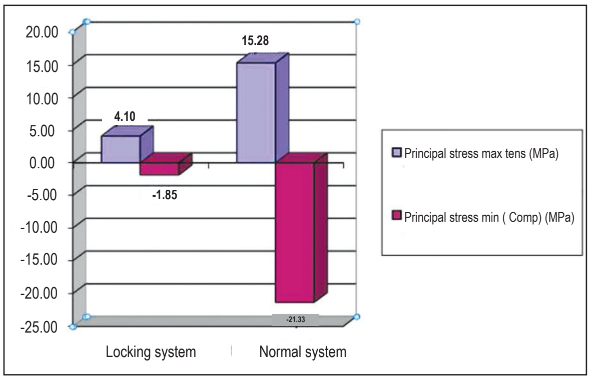

FIGURE 1: Principle stress max and principle stress min values in 25 mm length resected models.

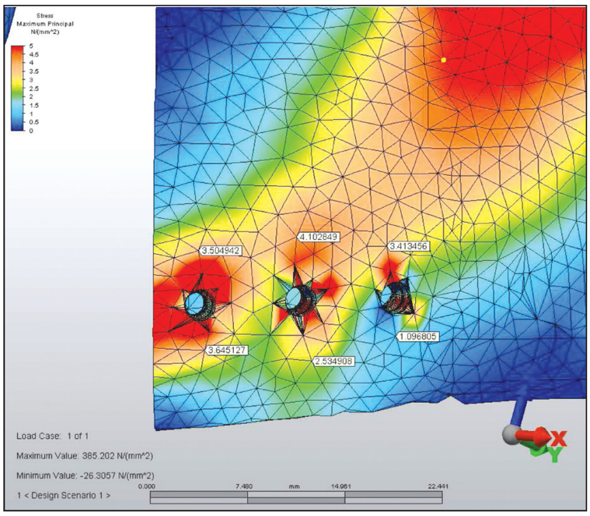

FIGURE 2: Principle stress max value in proximal cortical bone in 25 mm length resected models.

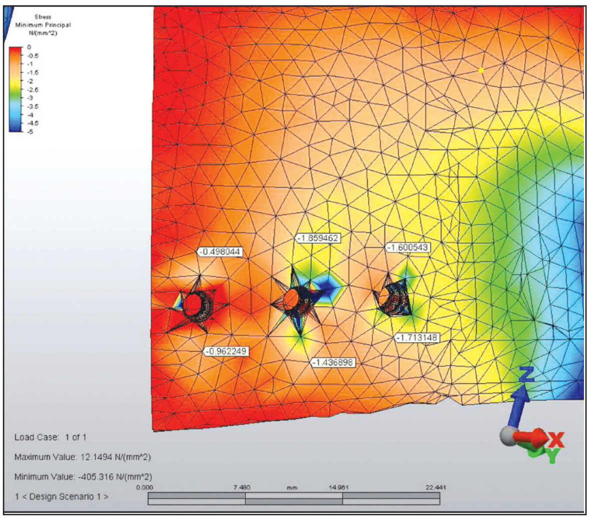

FIGURE 3: Principle stress min value in proximal cortical bone in 25 mm length resected models.

under appropriate loading condition (Table 3, Table 4) (Figure 4, Figure 5, Figure 6).

VON MISES VALUES ON SCREWS

The highest Von Misses values in the locking screw neck in 25 mm length resected models was found in the middle screw (34.90 MPa) of the proximal segment (Table 5) (Figure 7).

The highest Von Misses values in the locking screw neck in 50 mm length resected models was found in the middle screw (26.35 MPa) of the distal segment (Table 5) (Figure 8).

VON MISES VALUES ON PLATES

The highest Von Misses values in the locking plate in 25 mm length resected models was found (7.42 MPa) in the proximal segment. The highest Von Misses values in the locking plate in 50 mm length resected models was found (15.51 MPa) in the middle of the plate (Table 6) (Figure 9, Figure 10).

DISCUSSION

The mandible has a very important role in terms of functionality and aesthetics. This important structure is exposed to many pathologies that will disrupt its structural integrity. In the treatment of defects, many modifications have been made in both surgical and fixation techniques and materials to increase reconstructive success and stability.[3,10]

Two-point biomechanical test models and FEA method are the leading methods used to determine the biomechanical properties of fixation. Although biomechanical test models are suitable for biomechanical comparisons, FEA method is used to see force distributions in more detail.[11]

FEA was preferred in the present study due to its advantages such as reflecting its mechanical and physical properties of the material, application to all kinds of structures in dentistry, not restricting the number of materials, obtaining stress distributions and displacements together and sensitively, controlling the experimental model and changing the boundary conditions.[12,13] In many of the biomechanical and FEA studies, mastication forces were applied to reflect the forces of masticatory muscles and the resul-

TABLE 3: Principle stress max in proximal cortical bone in 50 mm length resected and using locking screws models.

	Distal			Proximal		
Screws	**3**	**2**	**1**	**1**	**2**	**3**
Principle stress max	0.15	1.52	0.90	1.47	0.06	3.55
	0.04	0.12	1.90	0.54	0.48	1.54

TABLE 4: Principle stress min in proximal cortical bone in 50 mm length resected and using locking screws models.

	Distal			Proximal		
Screws	**3**	**2**	**1**	**1**	**2**	**3**
Principle stress min	-0.85	-0.16	-0.30	-0.19	-2.71	-4.66
	-1.28	-1.31	-0.00	-0.69	-1.03	-2.61

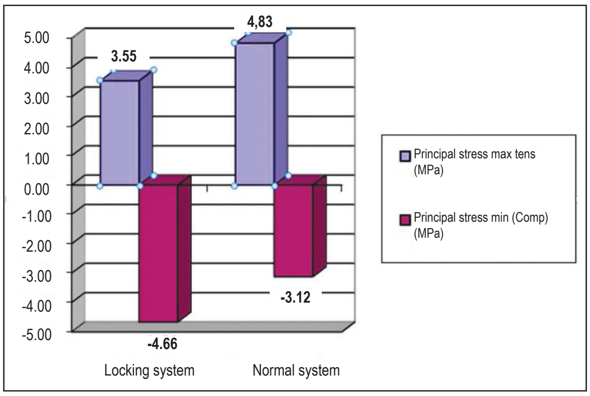

FIGURE 4: Principle stress max and principle stress min values in 50 mm length resected models.

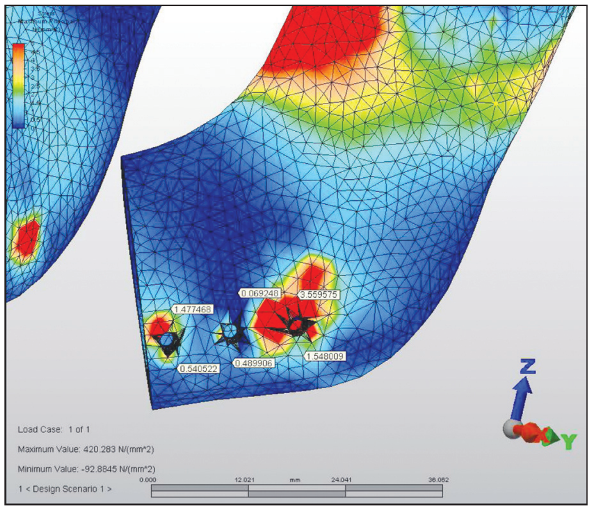

FIGURE 5: Principle stress max value in proximal cortical bone in 50 mm length resected models.

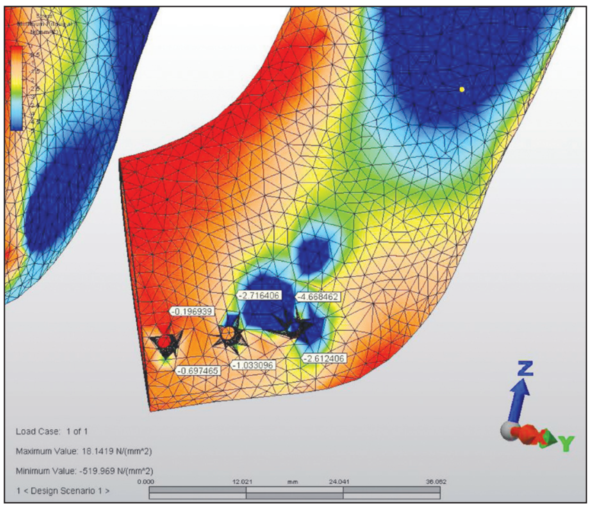

FIGURE 6: Principle stress min value in proximal cortical bone in 50 mm length resected models.

tant forces. In a biomechanical study in which only vertical and resultant force was applied, the system strengths under occlusal loading were tested in synthetic models with 4 cm lateral resection and fixed with different reconstruction plates. While there were not irreversible deformation or fracture on the plates, there were fractures in the synthetic mandible.[3] Haug et al. also demonstrated that reconstruction plates are resistant to incisal vertical loading but exhibit insufficient durability at contralateral molar loading. The reason for this was that torsional forces are very effective in plate deformation due to plate geometry (approximately 8 mm width, 2.5 mm thickness). They emphasized that plates with high vertical strength are more recipient to horizontal deformation due to superomedial effect of the pterygoid muscles and the inferolateral effect of the anterior digastric muscle.[14] In present study, for better evaluation, ef-

TABLE 5: Von Misses values in the locking screw neck in 25 mm and 50 mm length resected models.

		3	2	1	1	2	3
Short resection	Proximal (condylar part)				19.94	34.90	12.18
	Distal	7.92	7.80	12.63			
Long resection	Proximal (condylar part)				15.00	8.84	13.91
	Distal	7.88	26.35	23.28			

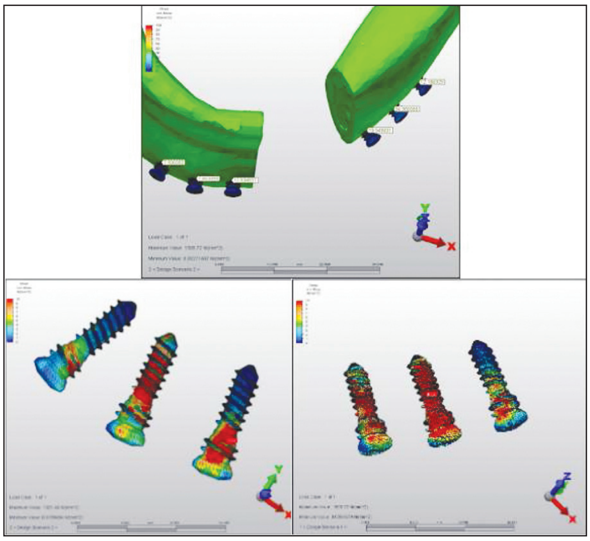

FIGURE 7: Von Misses values in the locking screw neck in 25 mm length resected models.

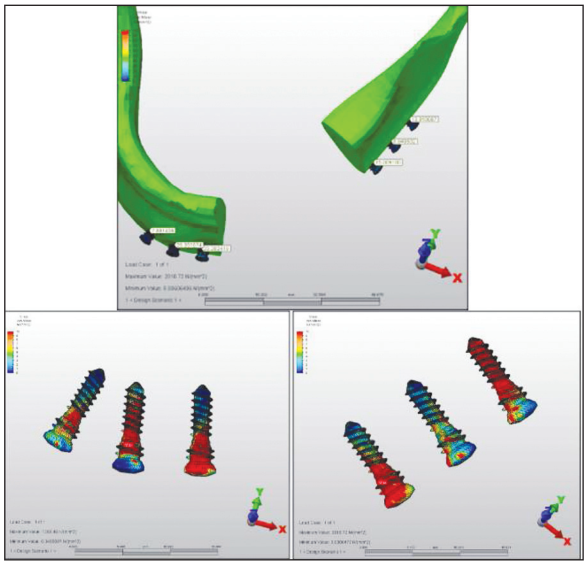

FIGURE 8: Von Misses values in the locking screw neck in 50 mm length resected models.

TABLE 6: Von Misses values in the locking plate in 25 mm and 50 mm length resected models.

	Distal		Middle of the plate	Proximal	
Short resection (25 mm length resected models)	2.28	2.43	5.56	7.42	3.88
Long resection (50 mm length resected models)	2.76	3.82	15.51	13.18	2.06

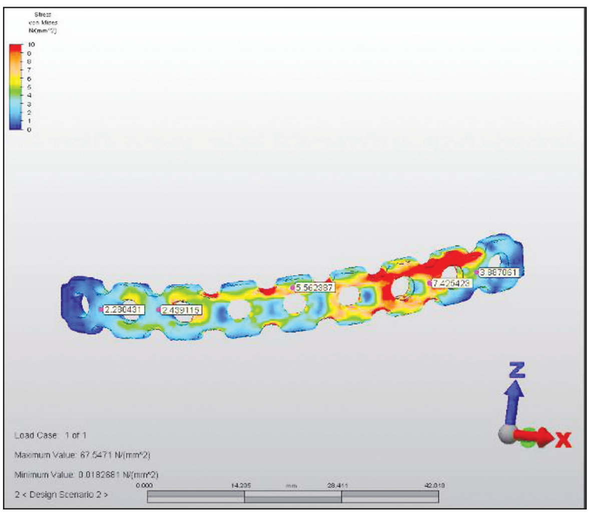

FIGURE 9: Von Misses values in the locking plate in 25 mm length resected models.

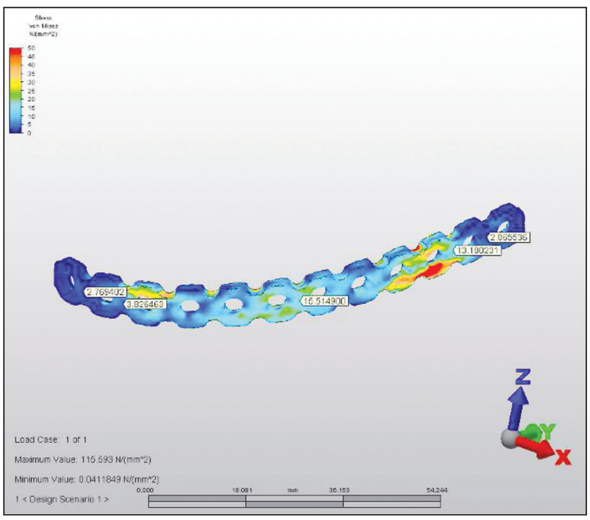

FIGURE 10: Von Misses values in the locking plate in 50 mm length resected models.

fects of different muscle vectors on different resection lengths, masticatory muscle strengths were reflected with the original magnitudes and vectors seen in the literature. So, mandibular movements are close to movements in clinic.[15]

Limit forces in healthy patients were used in the studies, although it's reported that the maximum muscle strength decreases to 186 N in patients who underwent resection and alloplastic reconstruction in the early period predicting that it will approach normal values in the future.[1,9,16,17] The effect of differences of force distribution on stability between the systems rather than quantitative values was evaluated in the present study. So, we prefered to test normal conditions according the results of the previous studies. Complication rates of reconstruction plate applications in lateral defects are reported to be between 5% and 10%.[18,19]

In some studies with a low number of cases, it has been reported that the rate of plate-related complications are in the range of 25-40%.[20,21]

However, Arden et al, who thought that the high failure rate in these series was caused by the inclusion of defects involving the corpus and ramus, showed that resected bone and soft tissue volume may affect the rate of plate-related complications. Plate related complications were occured in 62% of defects larger than 5 cm and 240 cm^3, while no complications in defects smaller than 5 cm and 240 cm^3 in their study. This difference shows that complication rates related to plate and screw systems may increase as the resection size increases and it is emphasized that the use of reconstruction plates alone should be limited in resections longer than 5 cm in order to achieve long-term stabilization.[22] In a similar study, it was emphasized that defect length is an important criterion for success.[23] In the present study, as the resection length increased; while tensile forces (principle stress max) decrease in the proximal segment except for the screw furthest from the resection area, there is no significant difference in distal segment. When compression forces (principle stress min) were examined, there is no significant difference in distal segment, while an increase were observed in the bone around the screws furthest from the resection area in the proximal segment. When the loads on the screws were examined; even there was no difference in the amount of total forces, there was a decrease in the proximal segment of the system and the 2 screws closest to the resection area and an increase in the 2 screws closest to the resection area in the distal segment. So, if the resection length increases, the load is more in the screws in the distal segment. When the loads on the plates were examined; while there was no difference in the distal segment, loading increased in the middle of the plate 3 times more and increased in the beginning of the proximal segment 2 times more.

CONCLUSION

In the present study, when the resection length increased, compression forces increased in the proximal segment and Von Misses values increased in the distal screws. The increase in the resection length had an important effect on the forces on the plates. And also, the highest Von Misses values were in middle of locking plate in both short and long resections. As compression forces increased in the proximal segment and the highest Von Misses values were in middle of plate; when length of the defect increases, it may be suggested that the middle of the plate should be designed thicker and plate configuration should be designed according to the resection type.

Source of Finance

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Conflict of Interest

No conflicts of interest between the authors and / or family members of the scientific and medical committee members or members of the potential conflicts of interest, counseling, expertise, working conditions, share holding and similar situations in any firm.

Authorship Contributions

Idea/Concept: *Burak Bayram;* ***Design:*** *Burak Bayram, Görkem Müftüoğlu;* ***Control/Supervision:*** *Görkem Müftüoğlu, Pelin Aydın;*

Data Collection and/or Processing: *Görkem Müftüoğlu, Burak Bayram;* ***Analysis and/or Interpretation:*** *Görkem Müftüoğlu, Pelin Aydın;* ***Literature Review:*** *Pelin Aydın, Görkem Müftüoğlu;* ***Writing the Article:*** *Görkem Müftüoğlu, Pelin Aydın;* ***Critical Review:*** *Burak Bayram;* ***References and Fundings:*** *Burak Bayram, Pelin Aydın;* ***Materials:*** *Görkem Müftüoğlu, Pelin Aydın.*

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