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DEPARTMENT OF ORAL AND MAXILLOFACIAL SURGERY

EVALUATION OF THE STRESSES CREATED BY DENTAL IMPLANTS IN THE MANDIBLE RECONSTRUCTED WITH FREE FIBULA FLAP BY FINITE ELEMENT ANALYSIS

DOCTOR OF PHILOSOPHY THESIS

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

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LIST OF SYMBOLS AND ABBREVIATIONS

2D:	Two Dimension
3D:	Three Dimension
a:	Acceleration
CAD:	Computer Aided Design
CT:	Computed Tomography
F:	Force
FEA:	Finite Element Analiysis
FM:	Fibular Model
kgf:	Kilogram Force
KAEK:	Klinik Araştırmalar Etik Kurulu
MPa:	Megapascal
m:	Mass
mm:	Milimetre
N:	Newton
P:	Pascal
TM:	Transplantation Model
Ti-6Al-4V:	Titanium-Aliminium-Valadium

ABSTRACT IN ENGLISH

Tanoğlu Y. (2022). Evaluation of the stresses created by dental implants in the mandible reconstructed with free fibula flap by finite element analysis. Yeditepe University, Faculty of Health Sciences, Department of Oral and Maxillofacial Surgery, Ph.D. Thesis. Istanbul.

Biomechanics are significant for bony regeneration and survival of implants in functional maxillary and mandibular reconstruction. The biological response of bones and accrued implant positioning affect implant longevity. There are sufficient studies on the number, diameter and stress distribution of implants in the native mandible and maxilla. However, there is limited information on the fibula free flap and studies are insufficient on the optimum number, position and distribution stresses of implants. The purpose of this study is to assess the stresses that occur after implant surgery with finite element analysis to determine the optimal implant number, size, diameter, and placement in the mandible reconstructed with fibula graft. Different 19 models were evaluated in the study so that accurate placement of implants in reconstructed mandible using fibular flaps to evaluate the optimum stress distributions under 120N vertical force. The Von Missess and Total deformation data obtained from the bicortical and monocortical placements of the implants that the present study placed in different lengths and positions in the mandible reconstructed with a free fibula flap. The results of the study, as the number of implants increases, the stress at the junction with the mandible decreases. Also, Total deformation decreases, Von Misses stress around implant-bone surface decreases. Monocortical or bicortical insertion; does not affect the Total deformation. High stress values were observed in the implants placed monocortical with a distance of 1 mm to the edge. There is a risk of perforation and dehiscence when placed 0.5 mm close to the edge. We think that studies about this issue will have positive effects on the patient's comfort and the active use of restoration and will reduce the complications that may occur after surgery. More studies are needed to evaluate the effects and consequences of stress.

Key Words: Fibula Free Flap, Dental Implant, Von Mises Stress, Total Deformation, Finite Element Analysis, Mandibular Reconstruction.

ÖZET

Tanoğlu Y. (2022). Serbest fibula flebi ile rekonstrukte edilen çenelerde, dental implantların yarattığı streslerin finite element analiz yöntemi ile değerlendirilmesi. Yeditepe Üniversitesi, Sağlık Bilimleri Enstitüsü, Ağız Diş ve Çene Cerrahisi Anabilim Dalı Doktora Tezi. İstanbul.

Biyomekanik, fonksiyonel maksiller ve mandibular rekonstrüksiyonlarda kemik rejenerasyonu ve implantların hayatta kalması için önemli bir faktördür. Kemiklerin biyolojik tepkisi ve implant konumlandırması, hem kemik hemde implant ömrünü etkiler. Doğal mandibula ve maksilladaki implantların sayısı, çapı ve stres dağılımı ile ilgili yeterli çalışma mevcuttur. Ancak fibula serbest flep hakkında sınırlı bilgi vardır ve implantların optimum sayısı, pozisyonu ve dağılım stresleri ile ilgili çalışmalar yetersizdir. Bu çalışmanın amacı, fibula grefti ile rekonstrükte edilen mandibulada optimal implant sayısı, boyutu, çapı ve yerleşimini belirlemek için implant cerrahisi sonrası oluşan streslerin sonlu elemanlar analizi ile değerlendirmektir. 120N dikey kuvvet altında optimum stres dağılımlarını değerlendirmek için fibular flep kullanılarak yeniden yapılandırılmış mandibulada implantların doğru yerleştirilmesi için çalışmada 19 farklı model değerlendirildi. Serbest fibula flebi ile rekonstrükte edilen mandibulada farklı uzunluk ve pozisyonlarda yerleştirilen implantların bikortikal ve monokortikal yerleşimlerinden elde edilen Von Missess ve Total deformasyon verileri ele alındı. Çalışmanın sonuçları değerlendirildiğinde; implant sayısı arttıkça mandibula ile birleşim yerindeki stresin azaldığı gözlenmektedir ve Total deformasyon değerleri azalmaktadır. Implant-kemik yüzeyi etrafındaki Von Misses stres gerilimi değerleri de sayı arttıkça azalmaktadır. İmplantların monokortikal veya bikortikal konumlandırılması Total deformasyon verilerini etkilemediği görülmektedir. Kenara 1 mm mesafe ile monokortikal yerleştirilen implantlarda yüksek stres değerleri gözlemlenmiştir. Kenara 0,5 mm yakın yerleştirildiğinde delinme ve ayrılma riski vardır. Bu konuda yapılacak çalışmaların hasta konforuna ve restorasyonun aktif kullanımına olumlu etkileri olacağını ve ameliyat sonrası oluşabilecek komplikasyonları azaltacağını düşünmekteyiz. Stresin etkilerini ve sonuçlarını değerlendirmek için daha fazla çalışmaya ihtiyaç vardır.

Anahtar Kelimeler: Serbest Fibula Flebi, Dental İmplant, Total Deformation, Sonlu Element Analizi, Von Mises Stres, Mandibular Rekonstruksiyon.

1. INTRODUCTION and PURPOSE

Surgical ablations of tumors, congenital malformations, trauma injuries, osteomyelitis, and osteoradionecrosis cause severe defects in the mandible or maxilla. Functional and aesthetic deficiencies are observed as a result of these defects, especially surgical procedures resulting in loss of basal bone, loss of alveolar bone, and teeth of the operated jaws. For this reason, it often leads to loss of chewing function, swallowing, speech, and lip support deficiencies.

With the development of microsurgery in the 1980s, reconstructive options in the lower and upper jaws expanded and offered surgeons wider reconstructive options. Osteocutaneous free flaps began to be used to correct segmental bone defects. Iliac crest, scapula, radius, and fibula can be included in these flaps with aesthetic and functional results. In terms of osteotomy and shaping capability, the donor site, bone quality and scope offer different advantages and disadvantages. In addition, these differences affect on the quantity of soft tissue and skin obtained.

On account of its excellent bone quantity and quality, the most common and versatile flap used in jaw reconstructions is the fibula flap. 25-30 cm linear bone structure also offers intraosseous and periosteal blood flow bringing in a well-vascularized structure. Sectional blood delivery by the way peroneal artery enables multiple osteotomies to construct three-dimensional outlines of missing sections. As a result, the devascularization of the individual segments is not observed. The thickness of the bone and its bicortical structure allows for primary masticatory forces and the use of osseointegrated implants. While allowing the removal of the flap from the donor area, it also allows the resection of the chin. Moreover, single or double skin islands containing the lateral side of the limb could be taken with the bone and it could be utilized to regenerate the outer skin of the neck and face, rimming the inside of the mouth, and covering the palate defects. Due to all these features, the fibula flap has great benefit in the reconstruction of segmental defects and it is the first choice in providing functional restoration.

Three-dimensional (3D) finite element stress analysis method, the ability to reflect the bone and surrounding tissue structures very close to reality, allowing the examination of the transmission and distribution mechanism of the stress in the implant and circumambient tissues. Moreover, this analysis is a valid and noninvasive method for evaluating the stresses caused by the forces applied to the bone. Also, it contains the fundamental structural features of the object and can be informed about the whole by examining the changes caused by the application of force with mathematical models in minor chunks of the object. Contrary to the fact that the prediction of the bone's response to stresses is difficult, finite element analysis has shown that it coincides with the findings observed in clinical cases. As a result, it is considered to be a realistic and successful method for stress analysis.

The purpose of maxillary and mandibular reconstructions is not only to provide aesthetics but also to provide a full oral function, in this way dental implants have gained an important place to provide the rehabilitation of the reconstructed jaws. The main purpose of dental implant applications and success; osteointegration and healthy gingival formation and appropriate implant selection, primary stability, bone volume, and quality is the right assessment. The number and location of implants are important for prognosis. Similar to the applicability of endosseous dental implants in full and partial edentulous mouths with high success rates, their effectiveness has also been proven in jaws with orofacial reconstruction, especially in implants placed on fibula flaps.

Although there are many mandibular reconstruction cases have been reconstructed with the fibula and have been published, there is no publication regarding the optimum implant number, diameter, length, and evaluation of these values by finite element analysis for fibula graft. The answer to the problem of length, which diameter is the most appropriate and the most appropriate distribution of the stresses on the graft is important in terms of the prognosis of the graft.

The purpose of the present study is to assess the stresses that occur after implant surgery with finite element analysis to determine the optimal implant number, size, diameter, and location in the mandible reconstructed with fibula graft.

2. LITERATURE REVIEW

2.1. Maxillofacial Defects

2.1.1. Introduction

Reconstructions at the oromandibular area are derived from resections such as malignant tumors, benign tumors, osteomyelitis, or osteoradionecrotic mandible remain challenging for surgeons today. Depending on the location of malignant tumors, mandibular or maxillary defects occur in the head and neck zone as a result of ablative surgeries. These distortions affect both shape and function and need a multidisciplinary route to solve cosmetic and functional outcomes. Detailed restructuring tactics necessitate the renovation of facial proportions, as well as height, width, and projection. To obtain ideal aesthetic and functional outcomes, reconstructive operations not only can restore the skeletal buttresses but also eliminate fistulas and restore the soft tissue envelope to ensure a base for dental rehabilitation. Renewal of the alveolar section permits the optimal settlement of dental implants and final rehabilitation with an implant supported prosthesis. Nowadays, ablative tumor surgery of the maxillofacial region demands not just a radical removal of a tumor with reconstruction. Moreover, the patient wishes for precise function and dental rehabilitation (1,2).

2.1.2. Etiology

Deficiency or disorders of facial components related to stomatognathic structures are called maxillofacial defects. Congenital, developmental, and acquired factors play a role in the etiology of maxillofacial defects. These factors can be classified as congenital defects, developmental defects, and acquired defects (3,4,5).

The decrement of teeth of the jaw bone and alveolar bone can accompany significant impairment of mastication. Serious oromandibular bone defects because of surgical removal of tumors, congenital disorders, trauma, injury, atrophy, osteoradionecrosis, or osteomyelitis provide a route to aesthetic and functional deficiency, for example, facial contour deterioration, swallowing disorder, and impaired functions of speech, malocclusion, and saliva retention (6,7,8).

The first goal of oromandibular restoration should be to renovate aesthetics and also, precise oral function (9). The main goals of this reconstruction in the oromandibular zone are would coverage, restore the permanency of jaws, promotion of the airway, restore facial contour, and provision of a biological base for dental rehabilitation (10,11,12).

In the past 20 years, free tissue transfers and dental implants have resulted in considerable improvements in form and function. Modern surgical techniques using free flaps provide acceptable results regarding the repair of hard and soft tissue defects, maintaining jawbone integrity and tongue shape. Free microvascular flaps can be easily used in the restoration of both intraoral and extraoral soft tissue losses by being prepared as osteomuscular including the bone as well as the periosteum and attached muscles, or as osteomyocutaneous flaps including the superficial skin tissue. The development of free microvascular flap techniques has allowed more predictable and successful results in the repair of large and complex defects in both bone and soft tissue. On the other hand, an acceptable facial appearance, speaking ability, and chewing function should be provided in order to maintain the self-confidence and psychological health of the patient after cancer treatment (1,13,14).

2.2. Types of Reconstruction

The optimal approach aims to reconstruct the native contour as much as possible. In order to achieve that bone grafts, alloplastic materials, distraction osteogenesis, pedicle flaps, and microsurgical flaps (iliac, tibial, fibula flaps) can be applied. These flaps can maintain enough soft and bone tissue to solve extraoral and intraoral tissue defects.

Several factors come into play when determining which technic to choose;

- Intraoral and extraoral defects
- Size, type, and position of defects
- Defect and size of the soft tissue
- Remnant bone quality and quantity
- Quality of local vascularization
- Previous surgery (15).

In 1971, microvascular-based oromandibular reconstruction was firstly stated by Strauch (16). The following studies by Ostrup and Fredricson and Taylor indicate that both the iliac and rib crest could be transplanted to the mandible by the way of microsurgery. Flap failure incidence is meaningfully decreased for these procedures. (17,18). Where the extensive defect and palate involved situations, microvascular free bone flaps are the preferred way. It facilitates the flap to fit more precisely to the defect (19).

2.2.1. Fibula Free Flap

In 1975, free fibula flap (FFF) was first defined by Taylor et al. (18). In 1998 Hidalgo, this flap was used firstly for mandibular reconstruction (9). The fibula bone is a sufficiently long, thin, and non-load-bearing. In addition, the fibula has a continual tubular cross-section along its length. It also has a thick cortex (66% of the section). For this reason, this feature makes the fibula one of the vigorous bones in order to transfer (20). The fibula bone ensures almost 23-25 cm of bone which is enough to rebuilt mandibular or maxillary defects (21). Fibula bone has a periosteal blood procurement by the peroneal artery. It also has an endosteal supply from the nutrient artery making it feasible to carry out various osteotomies that provide no damage has been done to the periosteum (22).

The principal feature of the fibula free flap is its greatest length (25 cm, mean length of 17-18 cm), artery diameter (1.8-3 mm), vein diameter (2- 4 cm), and pedicle length (up to 12 cm). Because of its unique features, it has more advantages than other flaps. First of all, the free fibula flab ensures appropriate tissue for the synchronous reconstruction of bone and soft tissue defaults. Bringing this tissue to contaminated and irradiated areas with the minimum complication incidence between microsurgical flaps. The thickness of fibula, cortical bone height, and bicortical form of the shaft are optimum for long-range implant-borne prosthetic rehabilitation. The cortical thickness of fibula is excellent with respect to the scapula crest or the iliac crest (23,24).

The effectiveness of endosseous implants put down into fibula flaps for oromandibular reconstruction has been thoroughly verified (8,25). Indications of free fibula flap for mandibular and maxillar reconstruction are various and contain oncologic resections, traumatic injuries, congenital defects, osteomyelitis, osteoradionecrosis, and large vascular malformation. Reconstruction of the temporomandibular joint is the unusual indication of free fibula flaps which utilize the capability of to the blood supply to neighboring segments as cartilage grafts or by suturing the flap to the fibrocartilaginous disk (26,27,28).

Fibula flap advantages:

- Maintains appropriate tissue in order to perform simultaneous reconstruction of the body and soft tissue defects,
- Provide viable living tissue to contaminated and irradiated fields with the minimum complication incidence,
- Plentiful vascularization simplifies multiple osteotomies and conformation of the flap to the defect,
- Simultaneously two surgical teams can work to perform both ablation and reconstruction (25,29).

For most facial reconstructions, the vascularized free fibula flap has happened a flap of choice for several reasons:

- the facilitate of harvesting;
- the practicality of acquiring a , muscle, skin paddle or both;
- the presence of enough length and bone quality;
- the capability to double barrel the flap;
- the possibility chance of confident implant-supported dental rehabilitation;
- the existence of minimum donor site morbidity (30,31,32).

The rigid fixation technique utilizes lag screw fixation, external fixation appliances, staples, titanium tray fixation, diverse reconstruction plates, and mini plates. Most surgeons give priority to a single fixation procedure for insetting time, while lag screws be required to be associated with mini plates. In today's applications, for fibula lag screw fixation is not the first alternative of most reconstructive teams. Reconstructive surgery of the jaws with fibula flap the staples is rarely used in, as compared to their using in orthopedics. (33,34).

Reconstruction plate can be contoured prior to mandibular resection, processing as a template fixed to the residual mandibular abutments, within which the fibula is given a contour for following fixation with screws. Even though different ways have been informed in the literature, the valid method of setting bony fixation to the residuary mandible is the handling of plates and screws (35,36).

2.3. Endosseous Dental Implants

The effectiveness of endosseous implants inserted into alveolar bone for treathment has been throughly corroborated (8). Dental implants are being used to restore the mastication by the way of prosthetic replacement of the dentition. Rehabilitation with implants are usually leads to improved facial sight, mastication, and function of speech (37). Rehabilitation of occlusion and reconstruction of teeth and bone is very important in renovate quality of life. Endosseous dental implants have revolutionized reconstructive procedure in patients, that make possible to stabilize dental prostheses (38,39).

With the emergence of dental implants fibula free flap can be more convenient for achieving optimum prosthodontic aims using both removable and fixed prosthesis (40). Guided bone regeneration, distraction osteogenesis, autogenous grafts, and free flaps can be applied in atrophic or defected jawbone in order to implants can be placed. The most common of these are flaps originating from the tibia, iliac, especially the fibula (41).

The applicability of endosseous implants in fully and partially edentulous mouths and reconstructed jaws shows a high success rate today (42). Perlngvar Branemark defined implant integration and osteointegration with his experimental studies that he started in 1952 and changed the thought of Linkow et al. that fibrous connective tissue formation is necessary between implant and bone. Osteointegration has been defined as the structural and functional connection between healthy, living bone and the load-bearing implant surface (43). The significant factors affecting the success of endosseous implants are ensuring osseointegration, correct diagnosis, appropriate implant selection, precise application of surgical technique, and stress distribution (44).

Cortical bone compactness, height, and bicortical construction of fibula shaft are optimal for long-term implant-borne prosthetic rehabilitation (45,46). The potentiality of inserting implants in reconstructed fields with the fibula allows us to figure out the troubles related to dental restoration (8,29). According to Cabbar et al, bicortical ancorage better than monocortical. However, one patient at the immediate implantation showed infection signs and swelling 1 month after the free fibula flap surgery. No flap failures were observed but, one patient had FFF fracture in immediate implantation and this fracture caused two implant failure (47). The success rate of implants placed in fibula free flaps was related to several factors such as radiotherapy, poor oral hygiene, lack of cooperation, age and diameter of implants (48). According to Ryan s et al. several complications can be seen in implant application and post operation during the fibula flap reconstructions such as: prolonged wound healing, recurred soft tissue infections, implant failure, fibula failure, exposed bone around implant, intraoral dehiscence, plate fracture, trismus, peri implant inflammation (49).

The mechanism in charge of implant failures is not exactly understood and literature concerning the influences of several biomechanical parameters is inconclusive (50). Biomechanics are significant for bony regeneration and survival of implants, however there is limited study that has included on analysis of biomechanics to lead the ideal position of implants for fibular grafts (51). Implant applications in jaws reconstructed with fibula flap have been evaluated in the literature with the FEA (finite element analysis) method. However, studies evaluating stress in different numbers of different positions and location placement are lacking. For this reason, different models were evaluated over 19 models in the study so that accurate placement of implants in reconstructed jaws using fibular flaps to evaluate the optimum stress distributions.

2.3.1. The Timing of Implantation Procedure

Reconstruction of alveolar bone and basal jaw, teeth, and correction of occlusion plays a key role in reintegrating patients' quality of life. Unlike the reconstruction of other parts of the oral cavity, the repair of the obtained osseodental unit is intended to be similar to the preoperative one. Most of the ablations are performed in order to eliminate malignant tumors from the body. Cancer management may medically require surgical radiation therapy and chemotherapy. During this process, patients continue to receive radiotherapy chemotherapy or there may be medical requirements that they will need to see after the operation. Chemotherapy has progressed novel approaches targeted therapy to more specifically eliminate malignancy. Surgery and radiation remain the primary modes of treatment for most tumors for the reason that surgical resection of a tumor physically removes the massiveness malignant tissue and radiation localizes the morbidity to the specific area of the body. These have adverse effects on normal tissue such as cellular changes and reduced vascularity (52,53). Unfortunately, these chemotherapeutic agents are not selective so, unable to distinguish between normally dividing cells and malignant cells which are adversely affected by chemicals found in bonemarrow and those lining the oral cavity and gastrointestinal tract, because of their high proliferation rates (54). Oral implant applications in irradiated tissue are not contraindicated, but implant failure risks increase with losses up to 35%, while in non-irradiated bone survival proportion is 90% in most studies (55). Depending on the performing of implants, a primary implant is described as that which is placed during reconstructive surgery. Secondary implant in other words delayed implantation is placed in tissue after 6-12 month after reconstruction (56).

Positioning dental implants into the fibula during the primary reconstruction has better entry, Also interdental relationships are more easy to identify. Besides, in a briefer period of time oral rehabilitation can be achieved. On the other hand, preoperative evaluation becomes sophisticated and implants can be completely lost in the state of flap collapse. The risk of interference with or delay of oncological therapy, principally of postoperative irradiation is a common problem. Implant exposure and mucosal lesions are post-operative complications with implantation carried out at the same time as reconstructive and ablative surgery (57,58).

However, the optimal implant placement time is still contraversial for free fibula flap (FFF) procedures. In delayed implant placement, inserting implants a few years after in a fibula flap is more safer and reliable. The free fibula flap can change its format and receive the properties of the native bone, For this reason, a 6-month delay is trustworthy (20,47,59,60,61). Traditionally, dental implant placement is generally applied as a secondary implantation procedure (delayed placement). In this procedure, there is a latency period after the reconstruction surgery and then the implants are placed. Positioning of the implant is usually not implemented during the operation for some occasions: (1) a raised operation time increased anesthesia process and graft morbidity. (2) location and angulation of the inserted implants might be compromised, this causing to prosthetic challenges later on. (3) the graft itself may become a failure or in the scenario of a malignant tumor, additional resection may be obligatory due to recurrence. Therefore, it is more appropriate to place dental implants 6 months after radiation therapy (62,63).

2.3.2. Success and Risk Factors of Implants

Installment of endosseous implants points out important thriving treatment method in the reconstructed jaw, whether with a revascularized fibula or iliac crest flap. On the other hand, the implant failure rates are in the range of 5-7% for ordinary procedures and up to 21% in significant grafting operations throughout at least 5 years of function (64). The dimension of dental implants depends on the dimension of the bone (fibular height) and usually does not pass over 3,5-4,5 mm in diameter and 13 mm in height (65,66).

Nelson et al. (2007) applied four-implant system in 93 patients. They used smooth machined surface and a rough surface implants. Major distinctions were not seen in the success incidence of osseointegration (67). Heberer et al. (2010) investigate cancer patients who took radiation therapy with chemotherapy. After six months of adjuvant therapy, a total of 120 conventional and modified implants were inserted in the mandible of 20 patients. In the irradiated bone areas, both implants surfaces were immensely successful (68). Fenlon et al. (2012) examined 145 implants in 41 patients with operated on 47 flaps. As the survival of implants ensued they reported that a microrough surface is better than a macrorough or smooth surface (69).

Determined risk factors for implant failure are:

- Low bone density,
- Low primary stability,
- Overload,
- Short implants (70).

For this reason, sure implant stability is very important for an accomplished clinical outcome. The primary agent of implant stability is the mechanical features of the bone density near the implant site, and how the contact between the implant neck and the cortical bone is achieved (71). If we suppose the right surgical procedure and a useful implant style, at the time of surgery, the primary implant stability was defined by the bone (25).

2.4. Strenght Analiyzes

2.4.1. Basic Mechanical Concepts

Force; is an effect that change the direction of motion, speed, state or shape of objects. It is a vector quantity and has direction, duration, magnitude and type.

The force acting by other objects is called external force, and the action and reaction forces between various parts of the object are called internal force.

Formulated as "Force (F) = mass (m) x acceleration (a)"

Its unit is Newton (N) or kilogram force (kgf), 1 kgf is 9.8 N (72).

Strain: shape formed in unit size when force is applied to the object signifies the change. Objects undergo deformation under force, either elastic, plastic, or both. Elastic strain, the body returns to its original state when the force is removed. In plastic strain, the applied force is the stress that the object can withstand. If the force is greater than the force, fracture or rupture occurs in the object.

Strain value usually expressed as “ % ” . Equation as "Strain = change in size / original size" expressed. While stress is a vector force with direction and magnitude, but strain is not a force it is a scalar quantity (73,74).

Stress: is the reaction occurring in the unit area of the object against the externally applied forces. The stress inside the body is known as the force per unit surface.

Expressed as "Stress = Force / Area" in the formula. Unit is Pascal (P= N/m^2 or kg/cm^2)

In dentistry, due to the small size, it is usually Megapascal (MPa) is used. Forces acting on the body can create three different types of tension.

1. Tensile stress; It is the tension that stretches the material that occurs in a force teaching in the direction perpendicular to the surface.
2. Compressive stress; The force applied to compress the material.
3. Shear stress; It is the application of force to cause the material to slide in parallel and opposite directions to each other.

When force is applied to the object, stress types are not observed in isolation, three basic combined stress condition occurs (75,76).

Hooke Law; It is the law that states that the elongation in an object is proportional to the pulling force within certain limits.

The elongation that occurs in the object is directly proportional to the length and tensile force of the object, and inversely proportional to the modulus of elasticity and cross-sectional area (77).

Elastic Modulus (Young's modulus); It is the internal resistance of the objects to the unit elongation when the load is applied on the intermolecular attraction force. It is a measure of its resistance to strain under stress acting in only one direction, and different for each material. Objects with a high coefficient of elasticity are rigid materials and are resistant to deformation with their high internal resistance. As the modulus of elasticity increases, the stiffness of the object also increases. A body with a high modulus of elasticity undergoes less deformation with the same forces than a body with a low modulus of elasticity (78,79).

Poisson Ratio; It is the ratio of the longitudinal deformation that occurs in the material under a certain force to the cross-sectional deformation. In other words, it is the coefficient that relates the stress in one axis and the deformation that this stress will create on the other axes. For example, when the object is under a pressure force, a shortening of the object will be observed parallel to direction of the load, and an increase in length will be observed vertical to the direction of the force. Length of the object under tensile forces as it lengthens, its width becomes thinner (80).

Poisson's ratio = elongation in width / elongation in length

Equivalent Stress; It is the stress value of the material in one dimension, resulting from combinations of stresses in two or three dimensions. It is a displayable value (81,82).

2.4.2. Force Analysis Methods

When force is applied to the elements of any object, force analysis methods are used to determine the ideal shape of the object by redesigning the overstressed elements by seeing the regions where the stresses and forces are concentrated under the loads they are exposed to. In terms of ethical rules and clinical applicability, since it is more difficult to perform force analysis in biological tissues than in inanimate materials, it was preferred to create models of tissues. The model is based on tissues, organs, materials, and applied materials. The similarity of the forces with the direction, type, and size of the functional forces is important in order to obtain the results closest to reality (83).

Force Analysis Methods:

1. **(Strain Gauge) Force Analysis Method:** It is a method in which the amount of tension in the structure is determined by examining how the structural changes in the object stretched within the elastic limits change the electrical resistance of the structure
2. **Force Analysis Method with Radiotelemetry:** It is a method in which data is obtained and analyzed with hardware and software without the need for any material connection.
3. **Force Analysis with Holographic Interferometry:** It is a technique in which the three-dimensional image of the object is recorded using a laser beam. Nanometric deformations on the surface are analyzed by converting them to visible beams.

4. **Photoelastic Force Analysis Method:** It is an analysis method that enables direct observation of the tension by transforming the tensions resulting from the application of force into visible light patterns.
5. **Thermographic Force Analysis Method:** It is a method in which changes in temperature due to regular loadings on a homogeneous, isotropic material are examined and associated with the principal stresses in the material.
6. **Brittle Varnish Force Analysis Method:** It is a method in which information about the magnitude and direction of the stress is obtained by observing the cracks formed and force applied after firing a special varnish on the model
7. **Finite Element Analysis Method**

(84,85,86).

2.4.3. Finite Element Analysis

The main principle of the finite element analysis (FEA) method is to use a structure consisting of sub-regions defined as "finite elements". Complex geometric structures are transformed into a network structure in the computer environment. This structure consists of elements, nodes connected to them and boundary conditions (87).

It is necessary to use as many elements as possible in order to obtain the force distribution in the model with precision. According to a certain starting point, the coordinates of all nodes on the axes are determined and transferred to the computer. While creating the model, the poisson's ratio and the elastic modulus (young's modulus) values, which determine the material properties of the elements, are introduced to the computer program (88). In the model, matrices are formed for the change situations that occur by applying the simplest external factors and boundary conditions to the nodes, and these matrices are solved with the help of a computer. In this way, principal stresses, axial stresses, displacement values, deformation datas or equivalent stresses (equivalent principal stress) are obtained. While evaluating these data, the mechanical properties of the examined material are taken into consideration (82). With the finite element analysis method, 1, 2 or 3 dimensional analysis of an object can be performed. Although this mathematical analysis method was developed for engineering structural systems with complex geometry, it also finds use in dental biomechanics with the development of computer technology (89).

Biological changes such as apposition or resorption due to the amount of tension in the bone structure cannot be examined, since the models in finite element analyzes do not completely mimic the biological structures. The 100% osseointegration between bone and implant accepted in the studies is not actually observed and is cited as the main reason for the differences seen with in-vivo conditions (90,91).

The structure to be analyzed is transferred to the computer and its modeling is done with any CAD (computer aided design) program. The finite element analysis models consist of limited elements with different structures and numbers, and a network structure that converges at node points. Since the elements express the character and mechanical properties of the structure, their number is directly proportional to the reality complexity level of the structure. The number of elements, the structural character of the object, the previous biomechanical studies and the computer capacity to analyze are the determining factors. With the completion of the geometry of the structure to be examined, the mechanical properties of the forces or the acting structure are defined and boundary conditions are created (82,92). The differences in geometry and types together with the number of elements determine the complexity of the equation, that is, the solution difficulty. If the elements that make up the structure are identical, there will be only one equation for the solution. Solutions are easy with the use of simple elements. In FEA where the analysis of the body is made, the boundary conditions are included following the creation of the system equations containing the internal forces. Boundary conditions are created by adding new terms to existing equations or shifting existing ones to the right and left. The resulting stresses, strains and deformations are calculated from the displacements of the elements forming the structure (93,94).

In the structure created on the computer, the material properties and loading conditions of each element are defined. Since each element in the model carries all the features of the main structure, the integrity of the reactions of these elements under loading imitates the structure. For certain boundary conditions, when the equations are solved under certain forces, the nodal displacements are found and the stresses are calculated from these displacements. The obtained data are in the form of numerical and theoretical values in tables and graphics. Since it is very difficult to interpret the data in this way, visuals about the structural deterioration of the structure under the forces, the distribution of stresses, and different data are usually obtained in the computer environment (95,96).

FEA and fibula studies were generally performed with fixed number and position implants. In 2018 by Kyung Heo et al, the fibula reconstruction performed by mandibular implant-supported splint prosthesis was studied with the FEA method and stresses were evaluated. In 2020, Zhang H et al, placed the implants in the fibula and looked at the stresses that occur against the different positioning of the fibula in the vertical direction in the mandible. In 2019, Cheng K et al, examined the general stress distributions of fibular reconstructions of different sizes with FEA (51,97,98). Implant applications in jaws reconstructed with fibula flap have been evaluated in the literature with the FEA method. However, studies evaluating stress in different numbers of different positions and location placement are lacking.

Advantages of the FEA method over other methods;

• Repeatability of the work

• The analysis results can be obtained in a short time compared to the experimental.

• Creating realistic models with software

• Obtaining the desired number of different models from different materials

• Ability to precisely calculate stress distribution and displacements

• Ability to model solid structures with complex geometry

Disadvantages of the FEA method compared to other methods;

• Professional knowledge, evaluation ability and experience requirement to create a good finite element model.

• The complexity of organizing analysis results

• Ensuring that the mathematical model system is close to reality for accurate analysis.

• The application of real conditions to the solid model is limited by the capabilities of the computer and FEA software (99,100).

3. MATERIAL and METHOD

The clinical research ethics committee (KAEK) application file with the registration number "1682" belonging to our research project was reviewed by the committee on 10/07/2019. As a result of the examination carried out by the board, it was decided that the study was ethically and scientifically appropriate (KAEK Decision No: 1072).

The mandible of a patient who underwent hemi-mandibular resection and reconstructed with a fibula free flap was imaged in DICOM format with CT (Computed tomography). Raw DICOM data with a slice thickness of 1 mm were loaded into Mimics 12.1 software (Materialise, Leuven, Belgium), a software that can reconstruct images in a computer environment. Simplification and reformatting processes were performed on the images reconstructed with the software, and the model was transferred to the Geomagic 3D program in ".stl" format. With the Geomagic 3D (3D Systems, Rock Hill, SC, USA) program, the asymmetrical areas were created symmetrically on the three-dimensional model, and the modeling process was completed as a smooth surface consisting of elements with uniform proportions, and a three-dimensional computer-aided design model CAD (Computer Aided Design) was obtained. With SOLIDWORKS software (Dassault Systems Solid Works Corp, Waltham, MA, USA), implant models were prepared with 4 mm diameter, 8 mm, and 11.5 mm lengths in parallel structure and free from thread design. (Figure 3.1) In the creation and analysis of finite element models, Intel Xeon 2.40 GHz processor, 250 GB Hard Disk, and 8 GB RAM equipped Windows 10 64-bit operating system was used.

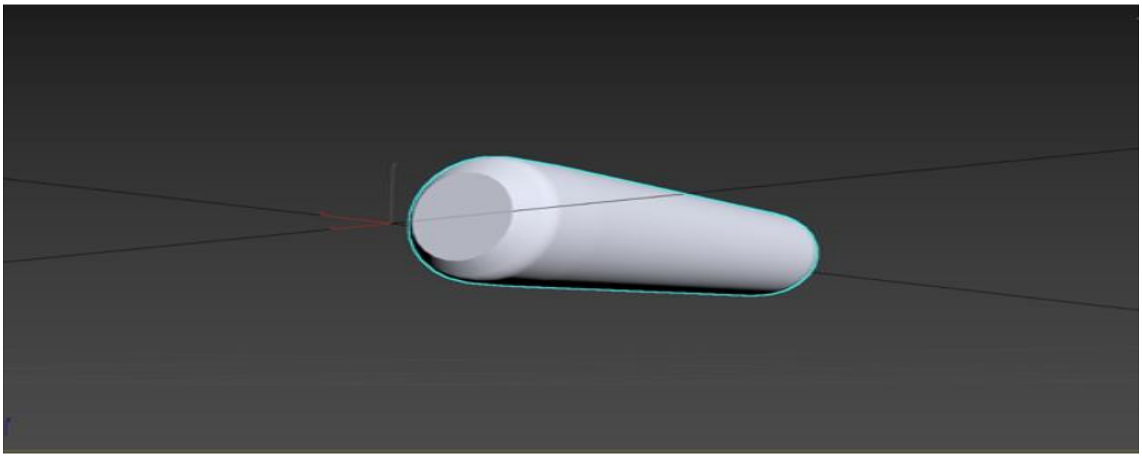


Figure 3.1. Dental Implant Model View

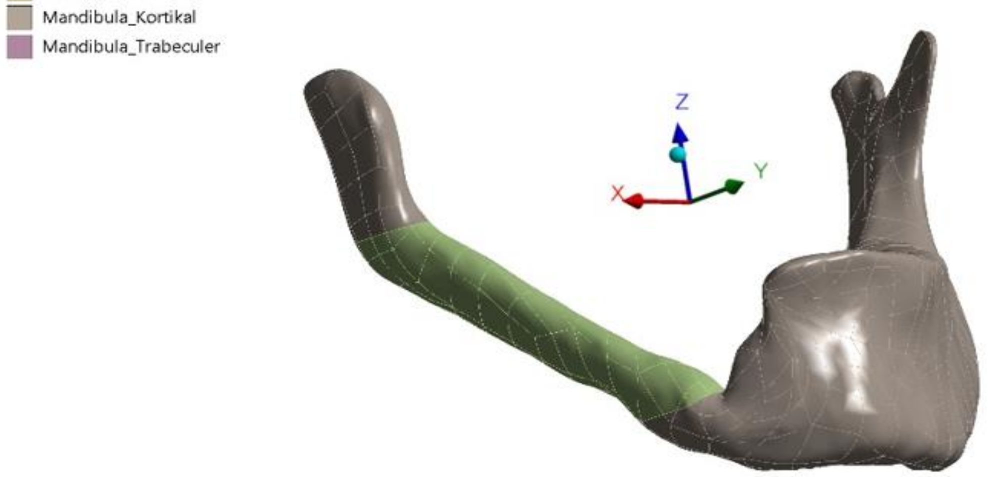


Figure 3.2. 3D view of model that reconstructed with fibula free flap.

Ti-6Al-4V alloy was used as implant material. The contact surfaces between the implant body and the bone were accepted as bounded, as representing osseointegration. Since the fibula and mandible have a linear elastic model, cortical and trabecular bones were specified as linear and homogeneous (101). Density, Modulus of Elasticity, and Poisson Ratio values of the materials shown in the table were used in the study. (102,103,104).

	Density *(g/cm^3)*	**Elastic Modul** *(MPa)*	**Poisson Ratio**
Mandible Cortical Bone	1,740	13700	0,3
Mandible Trabecular Bone	0,7	1370	0,3
Fibula Cortical Bone	2,1326	17000	0,3
Fibula Trabeculer Bone	0,7	700	0,3
Titanium Alloy (Ti-6Al-4V)	4.512	117000	0,35

Table 3.1. Density, Elastic Modul, and Poisson Ratio of materials.

In order to create boundary conditions in the model before force application, fixation was made from the condyle heads in such a way that each Degree of freedom (DOF) had '0' zero movement.

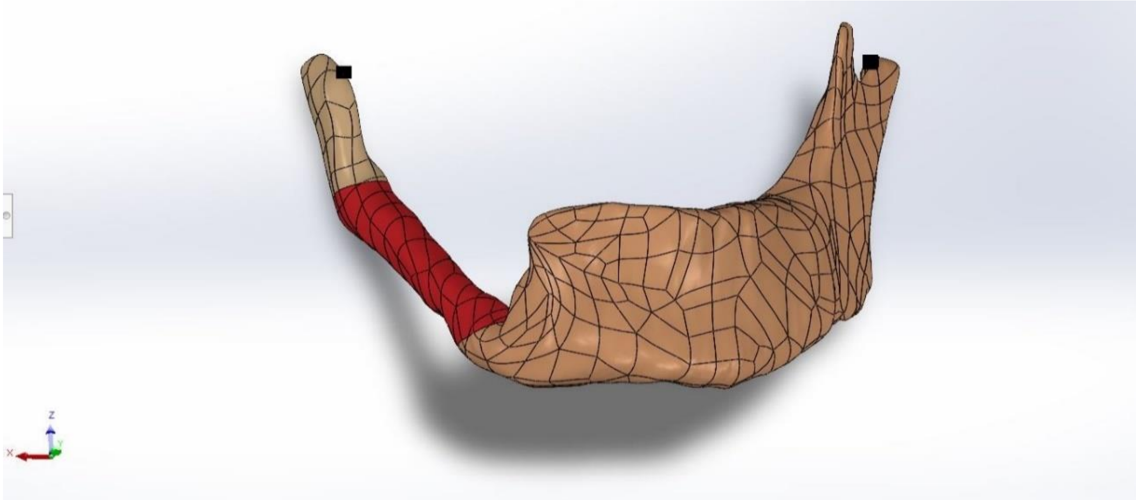


Figure 3.3. Image of the regions where the model is fixed.

CAD models were transferred to finite element analysis software to create loading conditions using ANSYS (Workbench 15.0; ANSYS Inc., Providence, RL, USA). With this software, the mesh structure was created and the three-dimensional node meshes were divided into 1 mm-2 mm elements. The implant and bone in contact were 1 mm, 1.5 mm in the fibula, and 2 mm in the rest of the model. The average number of nodes in the model was determined as 100000, and the number of elements was determined as 60000.

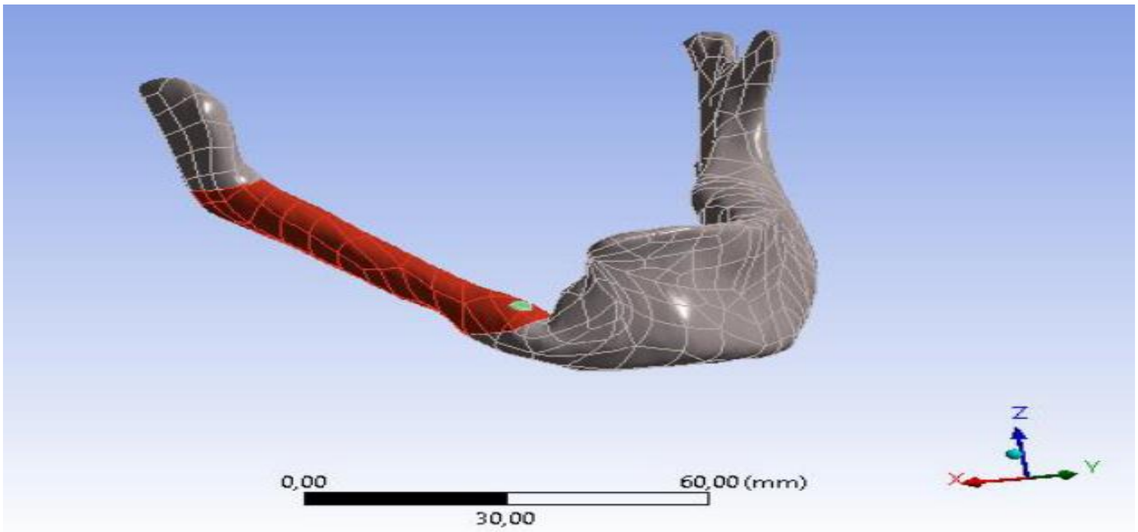


Figure 3.4. Meshed model image.

In the fixed models, 120 N (Newton) static resultant force was applied to the implants at 90° right angle for 1 second linearly. The resulting force distributions in models were evaluated with Equivalent Stress (Von Mises) data and Total Deformation data. In the models, the stresses occurring in the bone around the implant, the forces occurring at the junction of the fibula flap and the mandible, and the total deformation data in the jaw were evaluated.

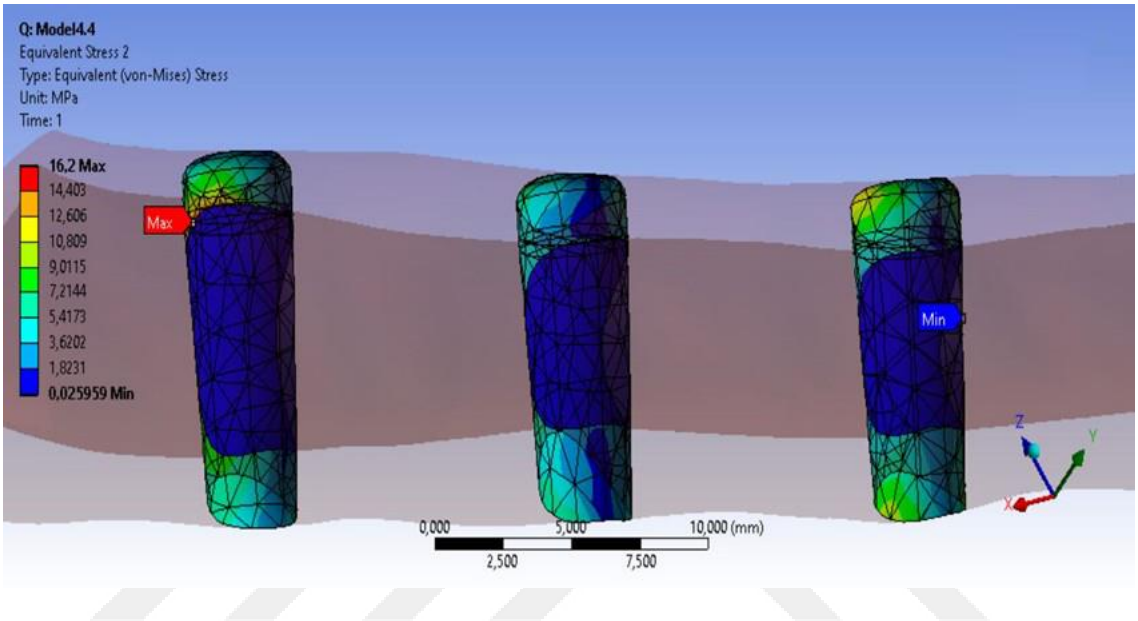


Figure 3.5. Von Mises stress distribution of implant-bone surfaces.

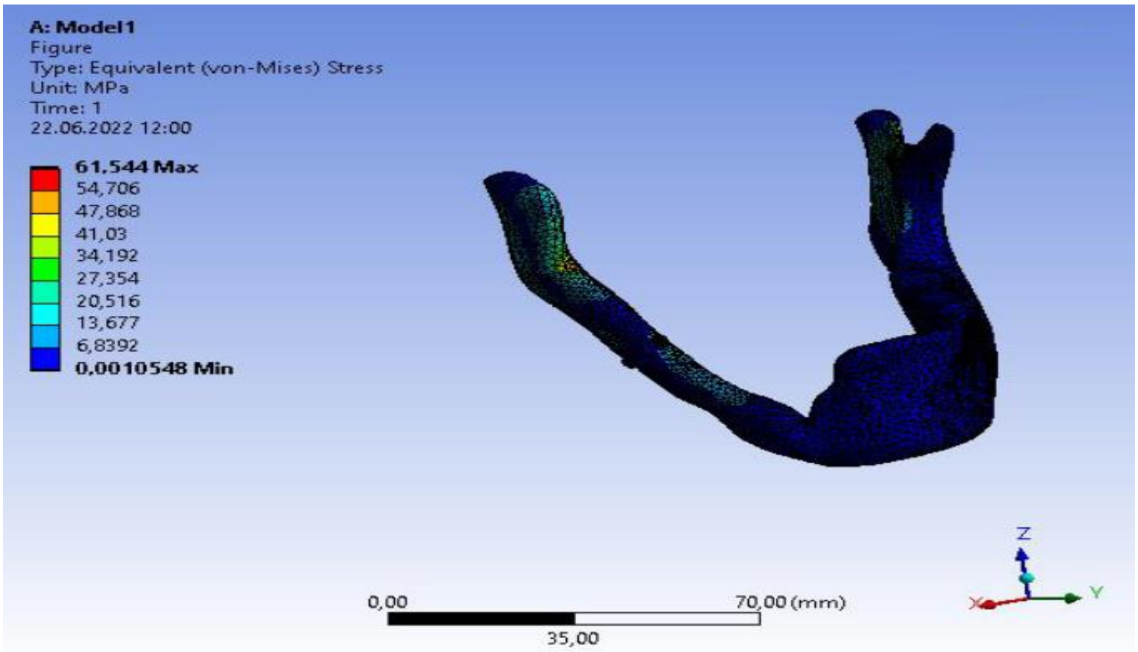


Figure 3.6. Von Mises stress distribution around implant and junctional region of fibula and mandible**.**

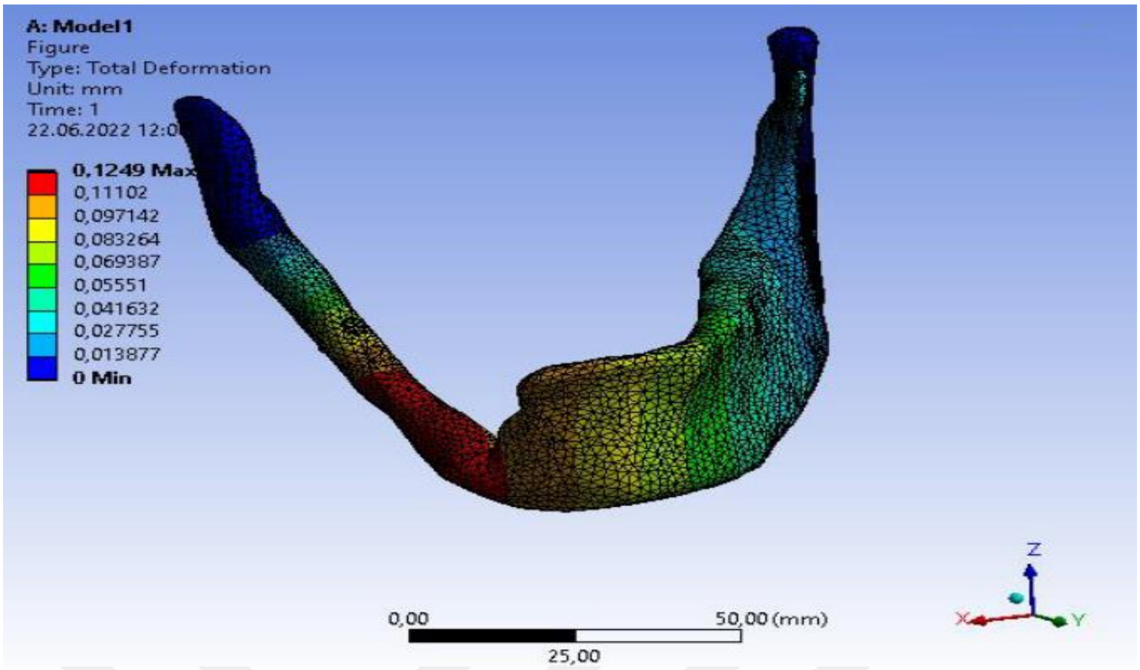


Figure 3.7. Total deformation values of the model.

In the present study, two implants with 4 mm diameter and a length of 8 mm, and 11.5 mm were designed with the Solidworks program. A total of 19 models were created with variations from 4 basic models of the mandible reconstructed with the fibula.

Model 1: Model with two implants 8 mm and 11.5 mm placed at monocortical and bicortical 3 mm intervals.

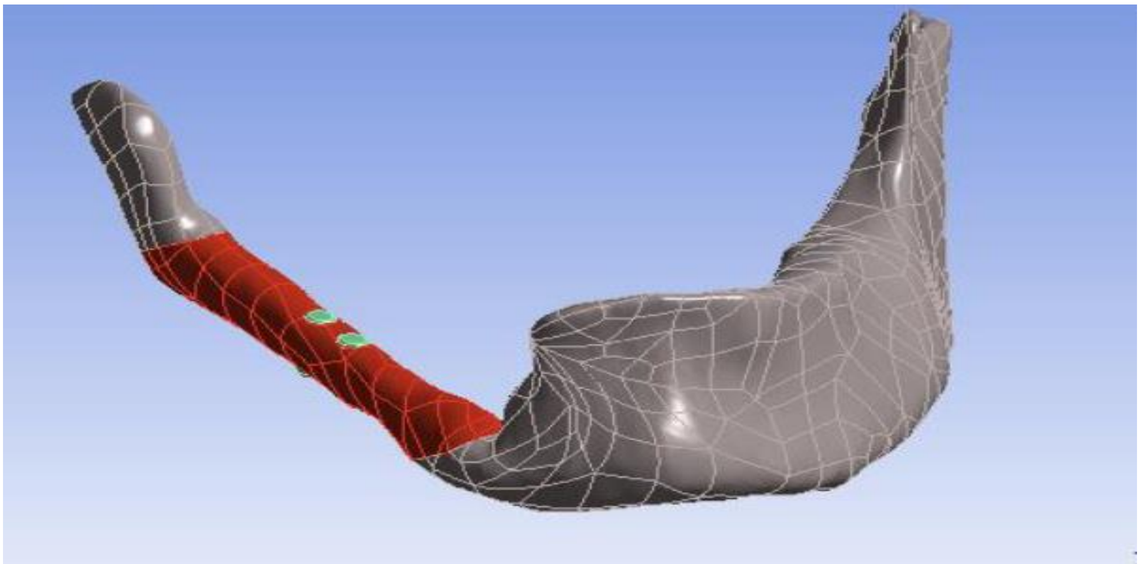
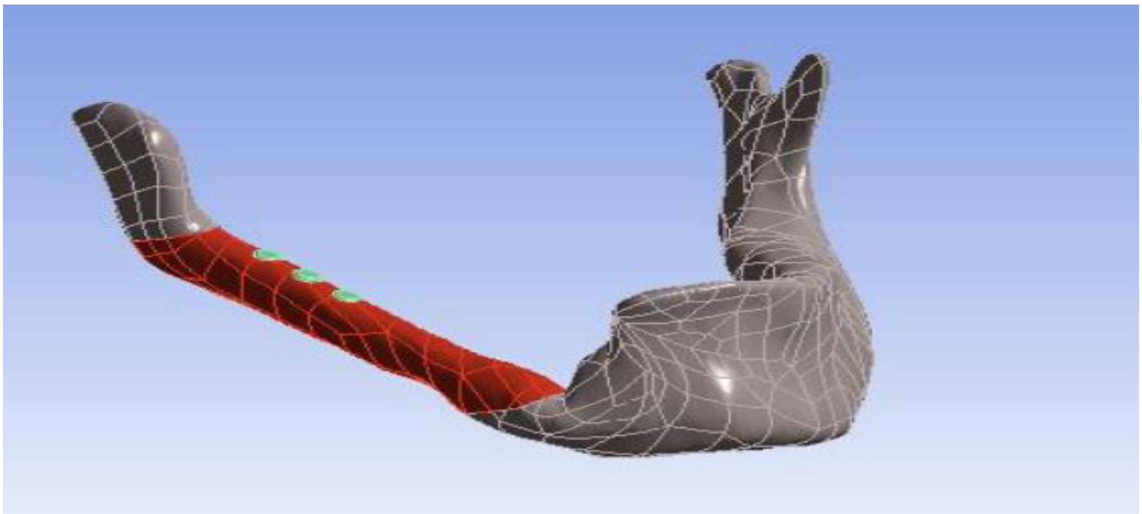
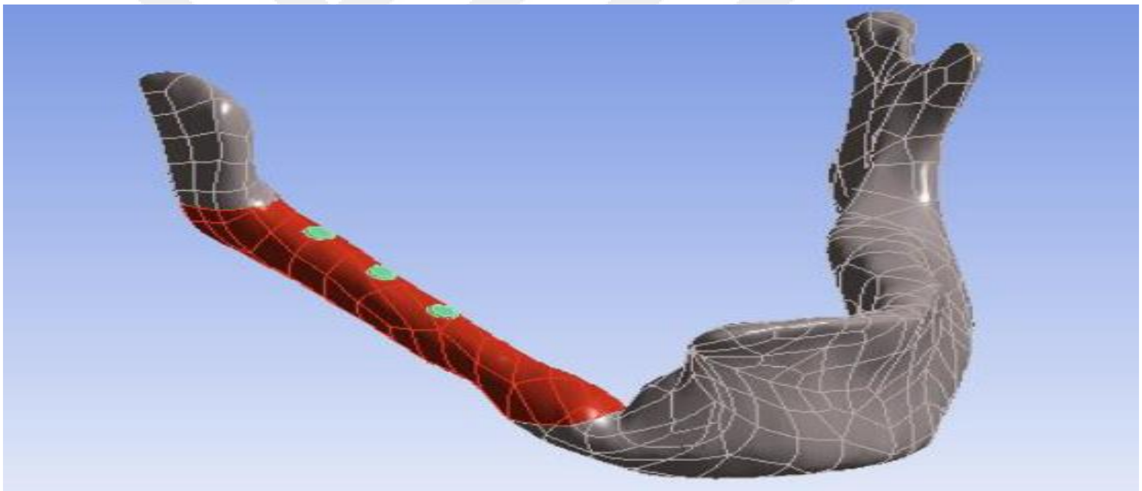


Figure 3.8. Model image of two implants with length of 8 mm and 11,5 mm one of which is placed mocortical and the other bicortically, 3 mm apart eachother.

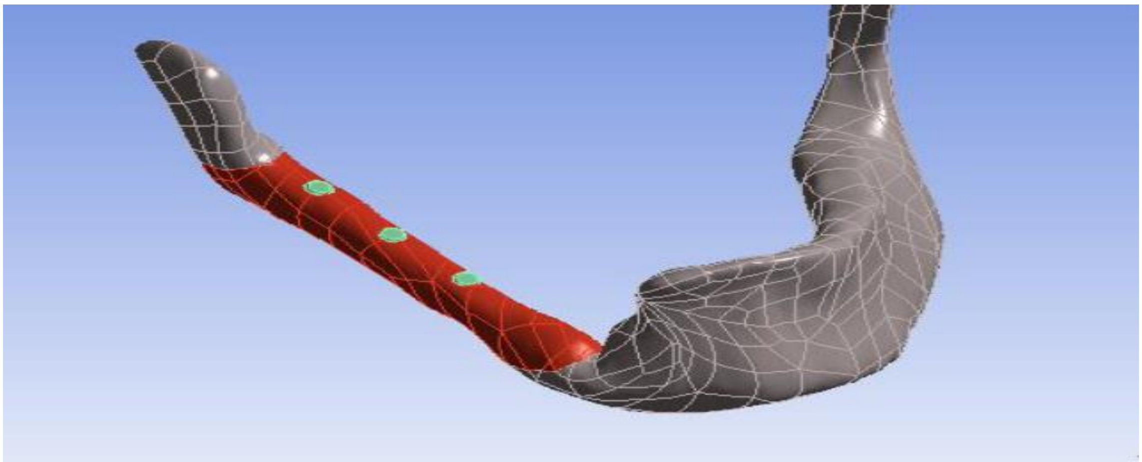
Model 2: In the middle of the fibula, implant placement is planned with 3 mm, 7 mm, 10 mm intervals. 3 implants are used in each model, a total of 6 models with monocortical and bicortical 3 mm, 7 mm, 10 mm positioning.



3mm

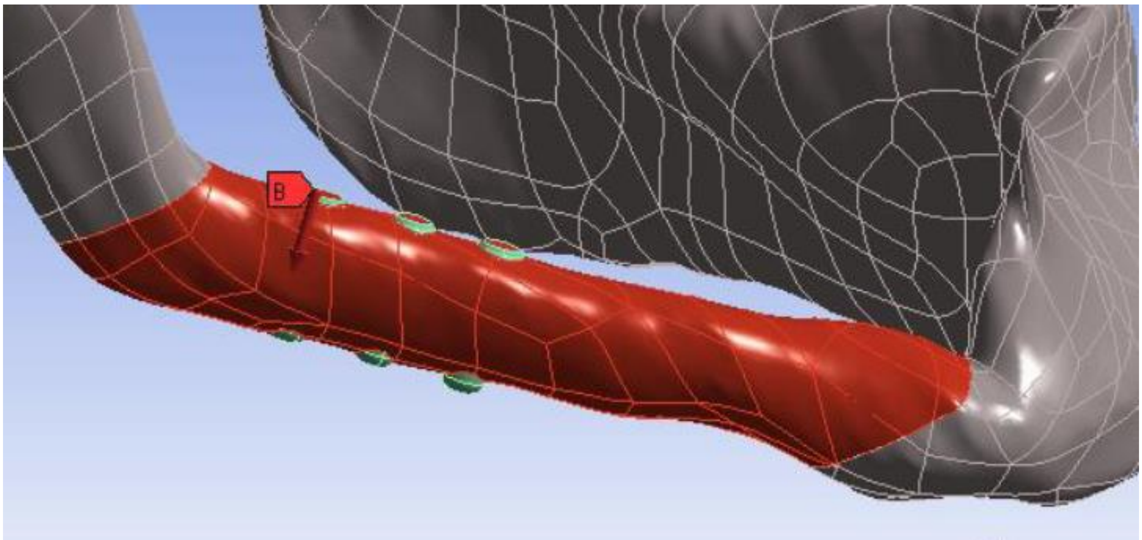


7mm

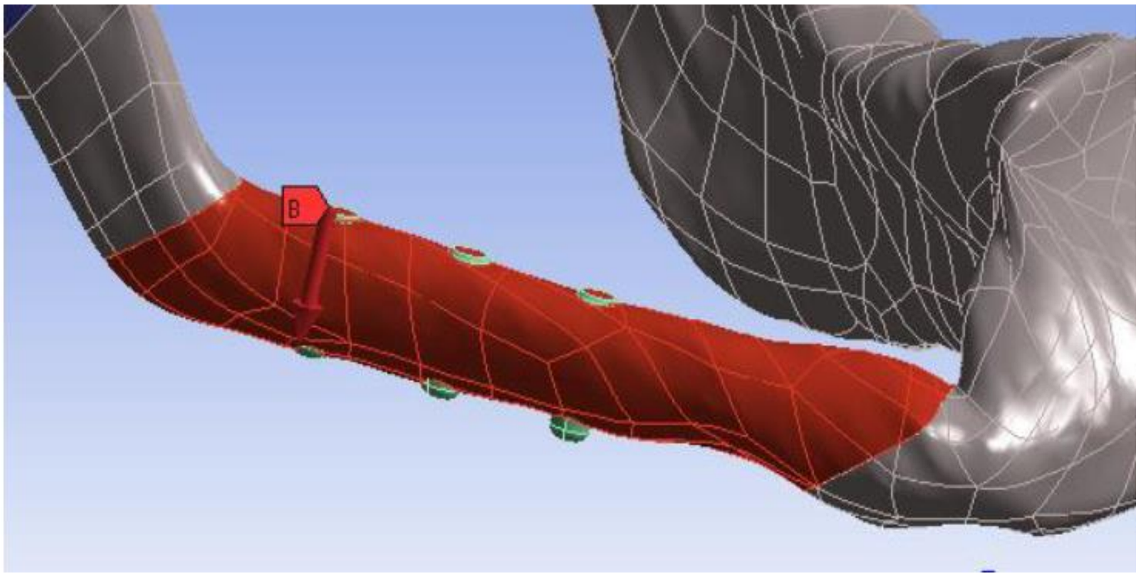


10mm

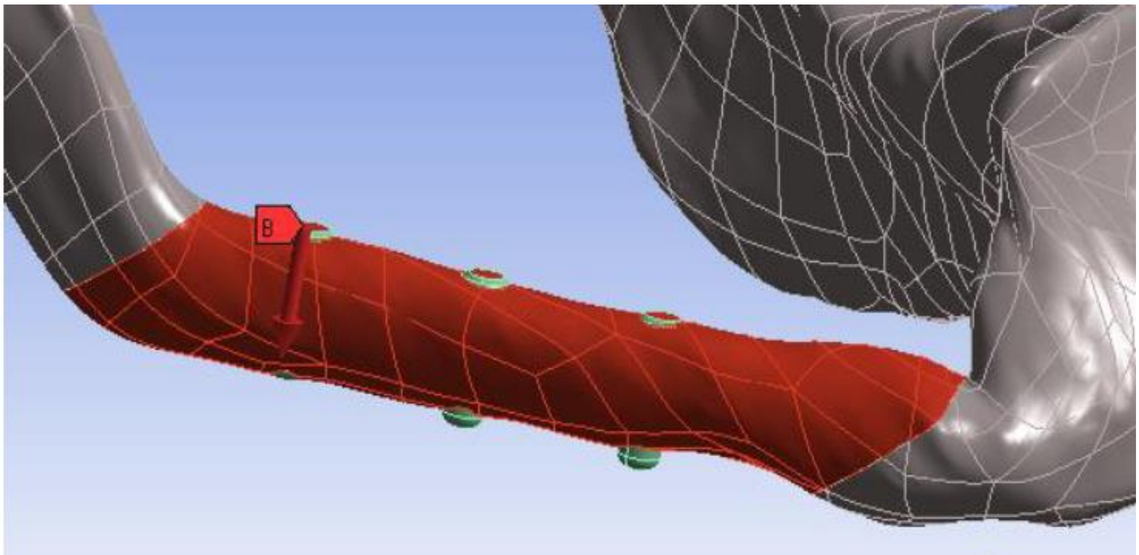
Figure 3.9. Implant models placed monocortically at 3 mm, 7 mm, 10 mm intervals.



3mm



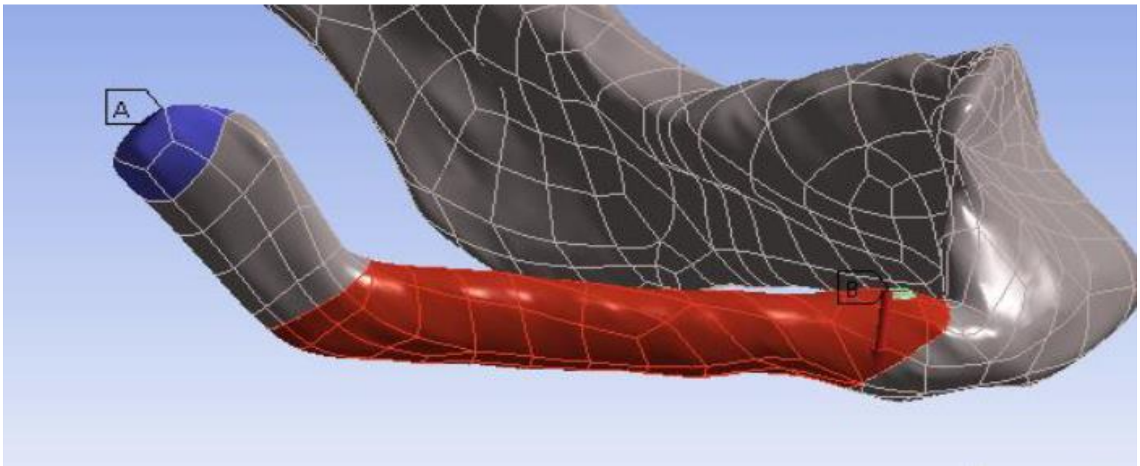
7mm



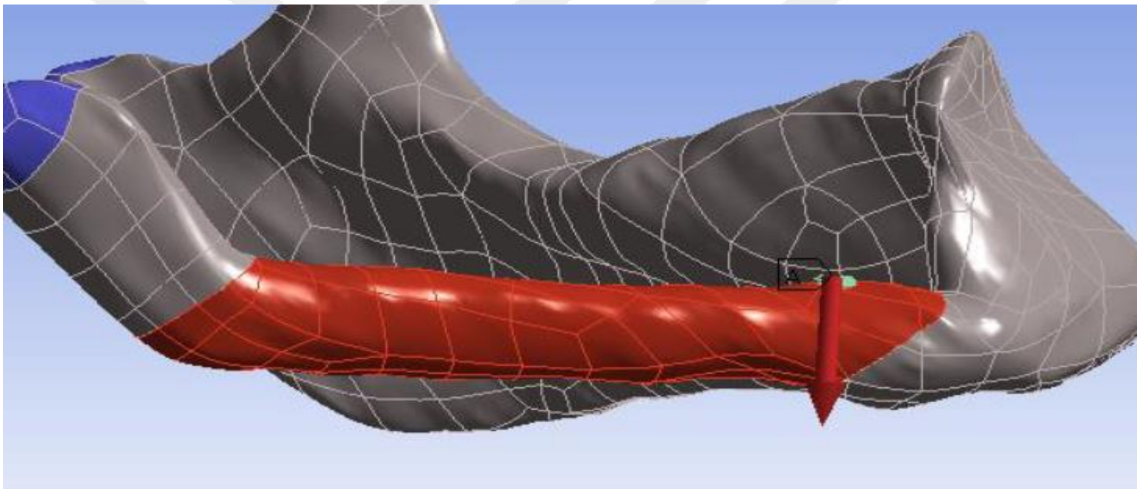
10mm

Figure 3.10. Implant models placed bicortically at 3 mm, 7 mm, 10 mm intervals.

Model 3: The implant placement was planned according to the proximity of the step (the mandible and fibula junction). A total of 6 models were created as monocortically and bicortically, distances of 3 mm, 7 mm, 10 mm from an implant to the step.



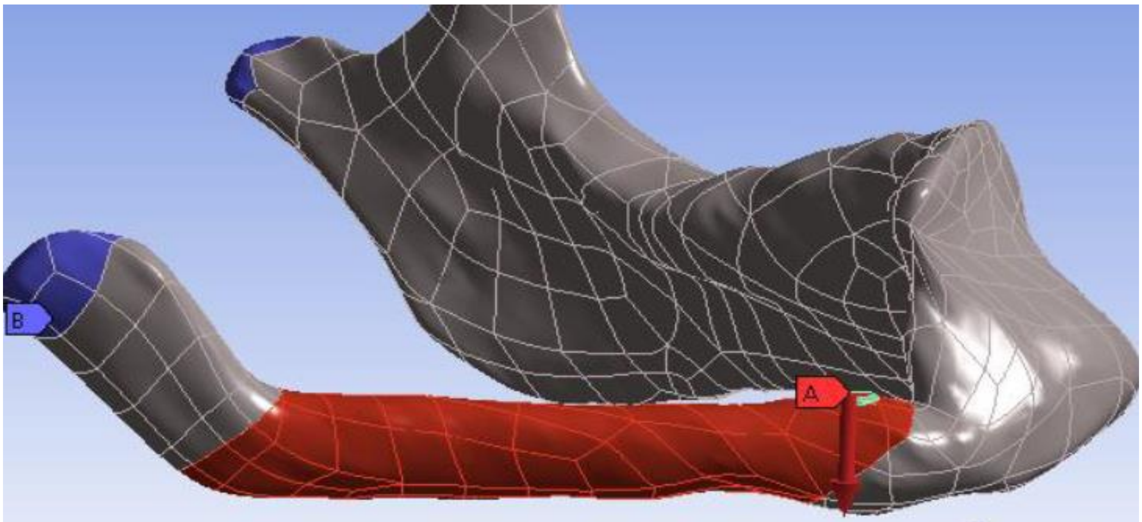
3mm



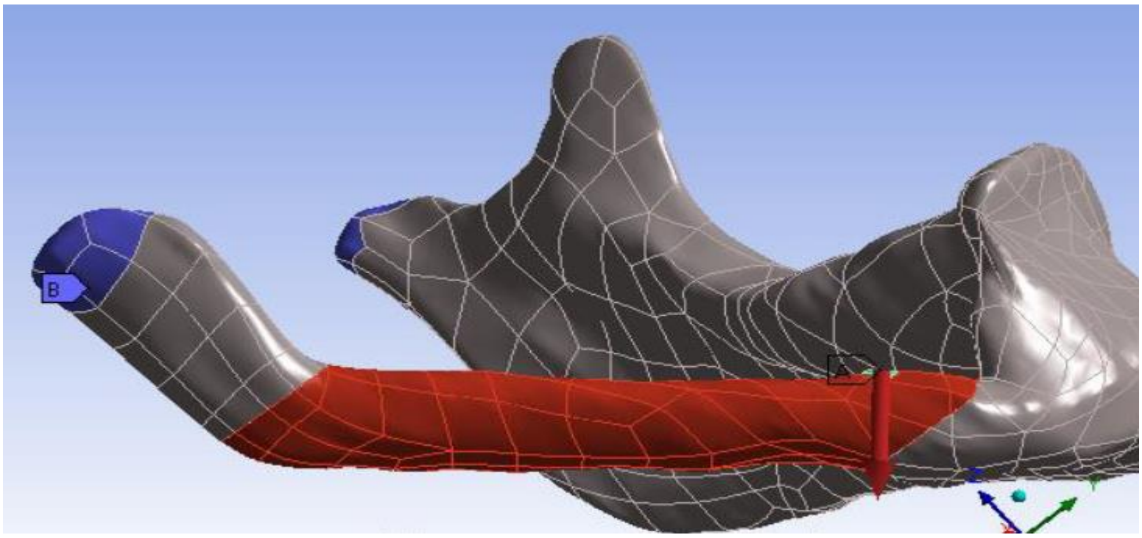
7mm

10mm

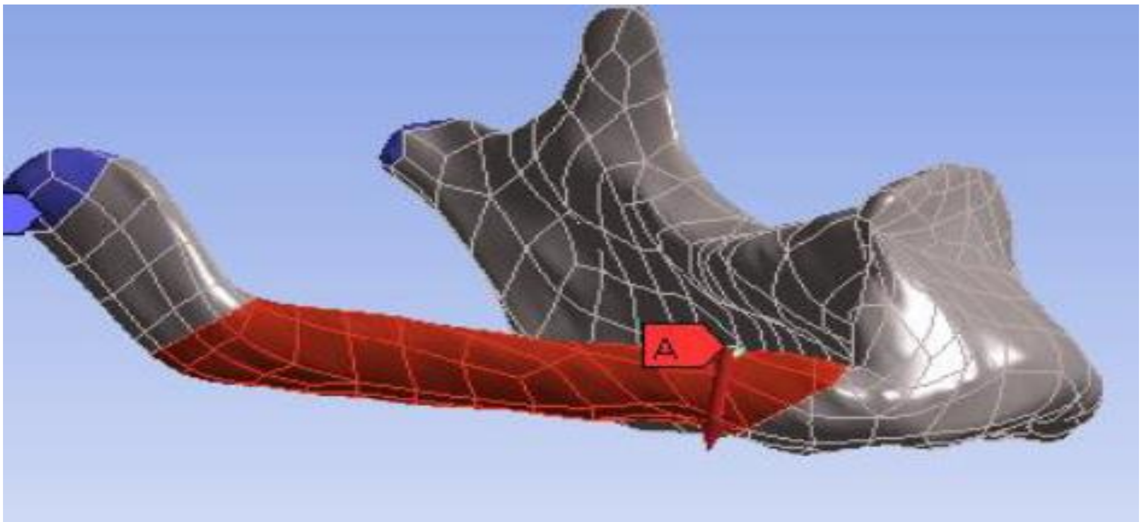
Figure 3.11. The image of the models placed monocortically at a distance of 3 mm, 7 mm, 10 mm to the step.



3mm



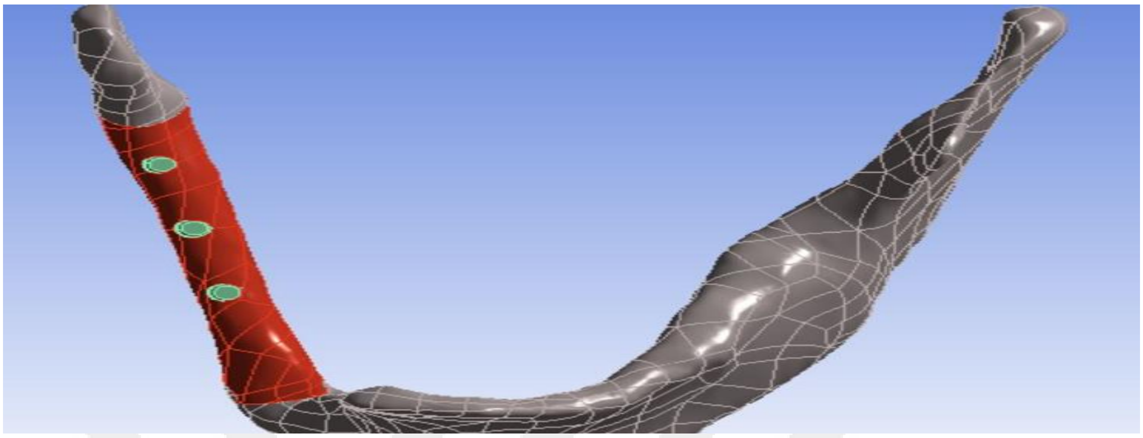
7mm



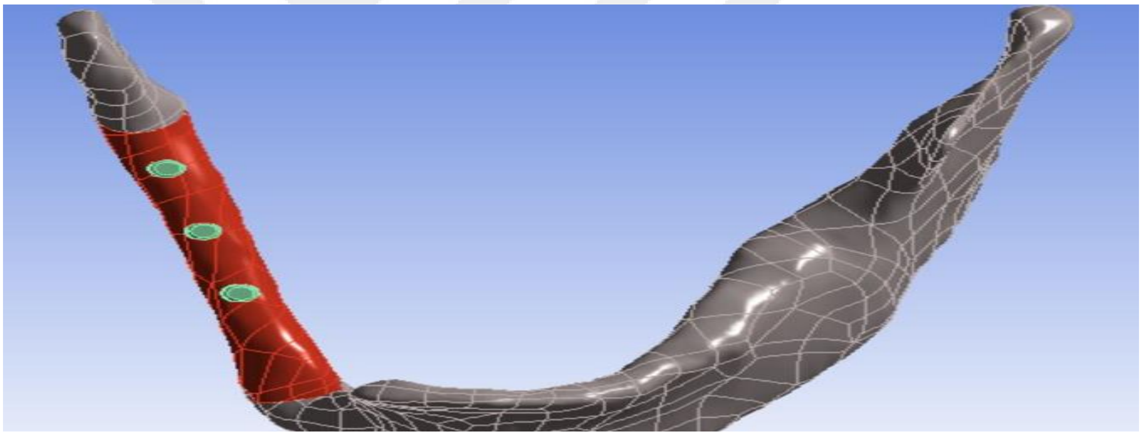
10mm

Figure 3.12. The image of the models placed bicortically at a distance of 3 mm, 7 mm, 10 mm to the step.

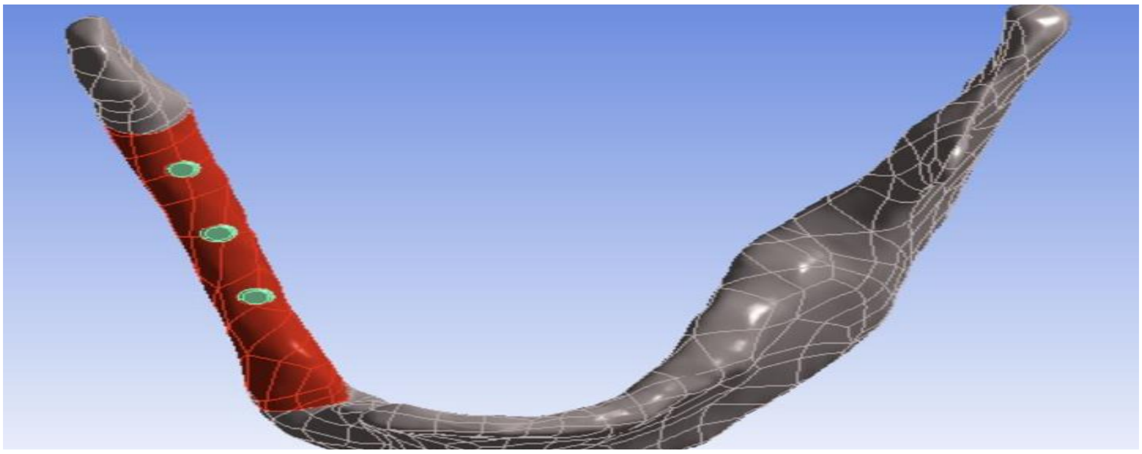
Model 4: The model was planned according to the distance to the edges of the fibula. The implants were placed at 10 mm intervals in the model. The implants were placed first mocortically and then bicortically at 0.5 mm, 1 mm, 2 mm distances from the edges, and a total of 6 models were created.



0.5 mm to the edge

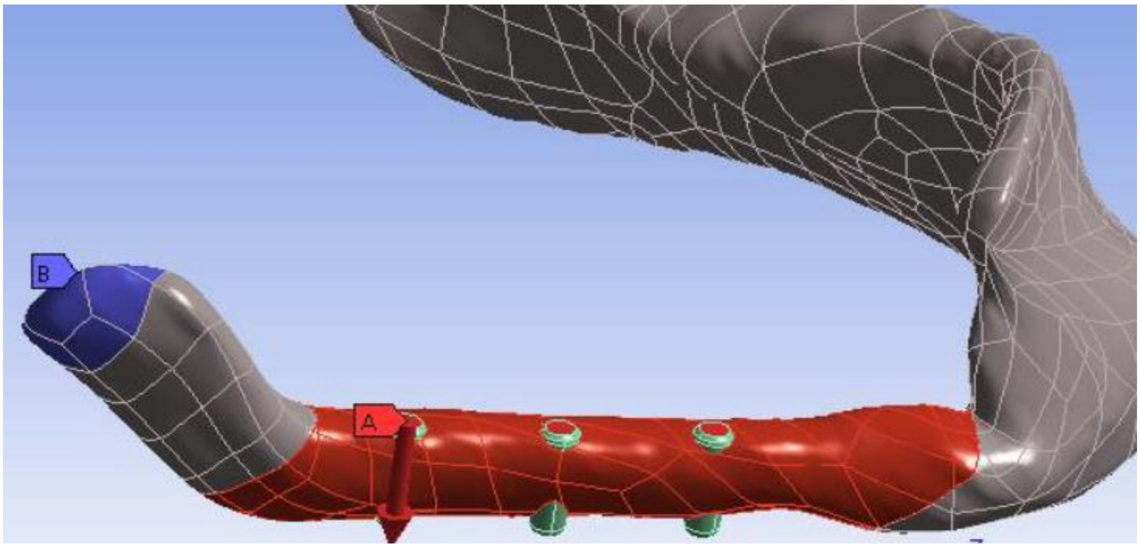


1 mm to the edge

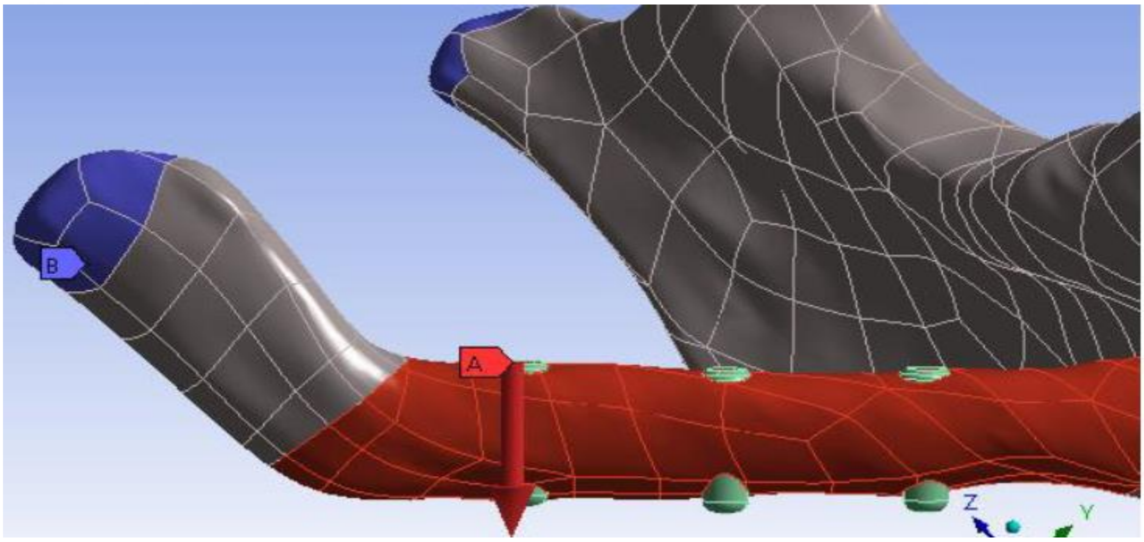


2 mm to the edge

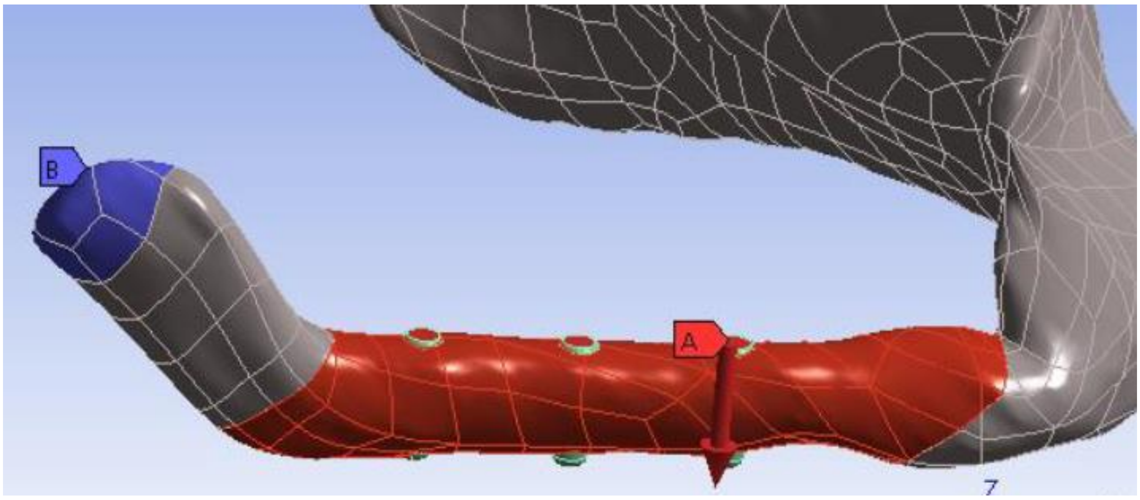
Figure 3.13. The image of the models placed monoortically at a distance to the edges 0.5 mm, 1 mm, 2 mm.



0,5 mm to the edge



1 mm to the edge



2 mm to the edge

Figure 3.14. The image of the models placed bicortically at a distance to the edges 0.5 mm, 1 mm, 2 mm.

3.1. Statistical Evaluation

Since the values obtained as a result of the finite element analysis are the result of mathematical calculations without variance, statistical analysis of these values is not performed. The results of the analysis were shown and interpreted as different Von Mises (Equivalent Stress) forces expressed by different colors on the color scale.

4. RESULTS

In the present study, stress distributions created in 19 different models as a result of the implementation of a resultant force of 120N to the implants at a right angle (vertical) were evaluated. The stresses around the surface where the implant comes into intercourse with the bone and the stresses created by the implants in the model were evaluated with Equivalent (Von Mises) Stress data. In addition, The Total Deformation data created by the implants in the model were evaluated.

In the evaluation, the analyses with Von Mises Stress and Total Deformation evaluations were handled separately, since their criteria were different.

Von Mises Stress evaluation was evaluated in terms of "MPa" in the highest values occurring in the bone and in the regions where they are located. Total Deformation data were evaluated in terms of "mm" by considering the concentrated areas in the model. Tables were made for the analysis results in the models, and bar graphs were created for comparison. The stress distributions on the models are shown in the figures.

4.1. Model 1 Evaluation

Von Mises Stress and Total Deformation values, which are caused by the application of 120N vertical force on two implants, one monocortical and the other bicortical placed with 3 mm intervals, are shown in (Figure 4.1), (Figure 4.2), and (Figure 4.3). In the model, the highest Von Mises Stress was observed as 61,544 MPa in the superiodistal position at the junction of the fibula and the ramus zone of the mandible. In the model, stress evaluations affecting the lingual and buccal surfaces were observed around the implants and on the superiomesial ridge of the medial implant.

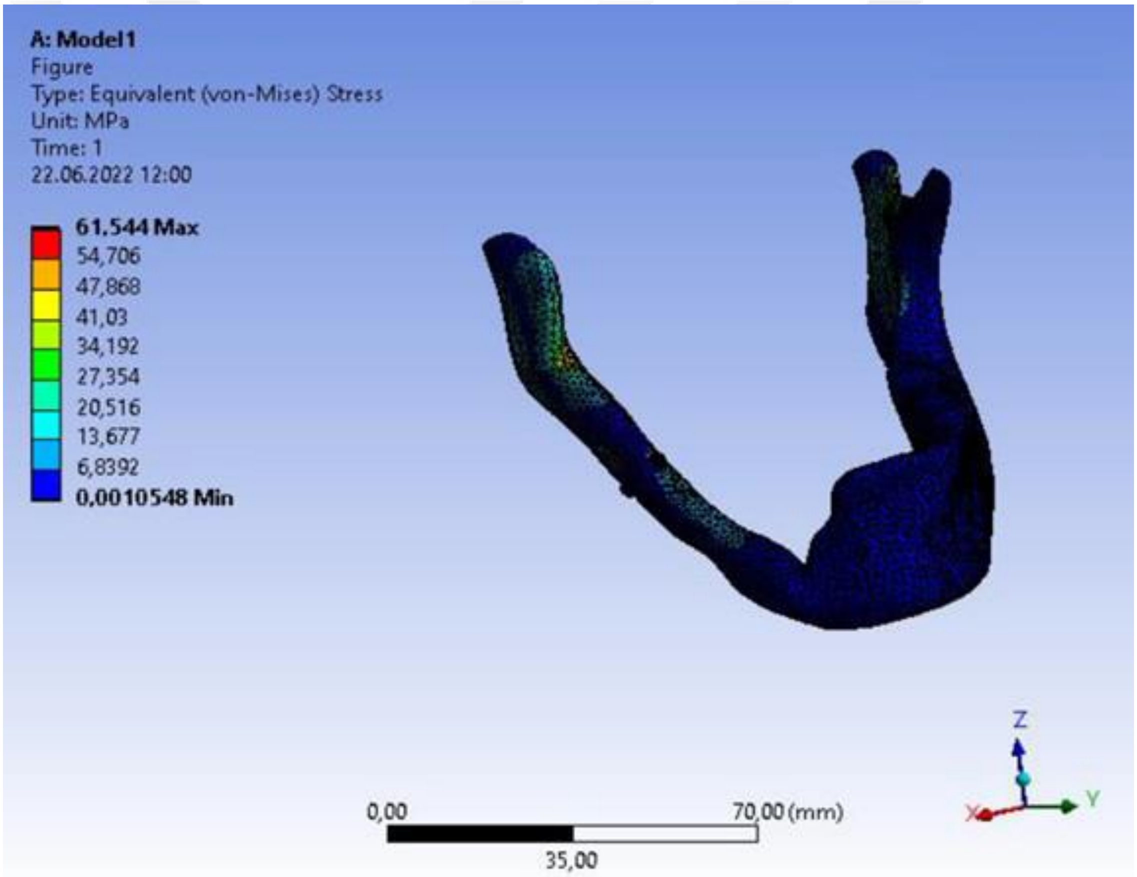


Figure 4.1. Equivalent (Von Mises) stress values in the model.

The highest Von Mises stress value around the implants was observed as 23,721 MPa in the cortical bone of the fibula, distal to the monocortical implant. The highest Von Mises stress value in the bicortically placed implant was measured as 14,450 MPa. The lowest stress value was observed in the implant located monocortically in the fibula trabecular bone.

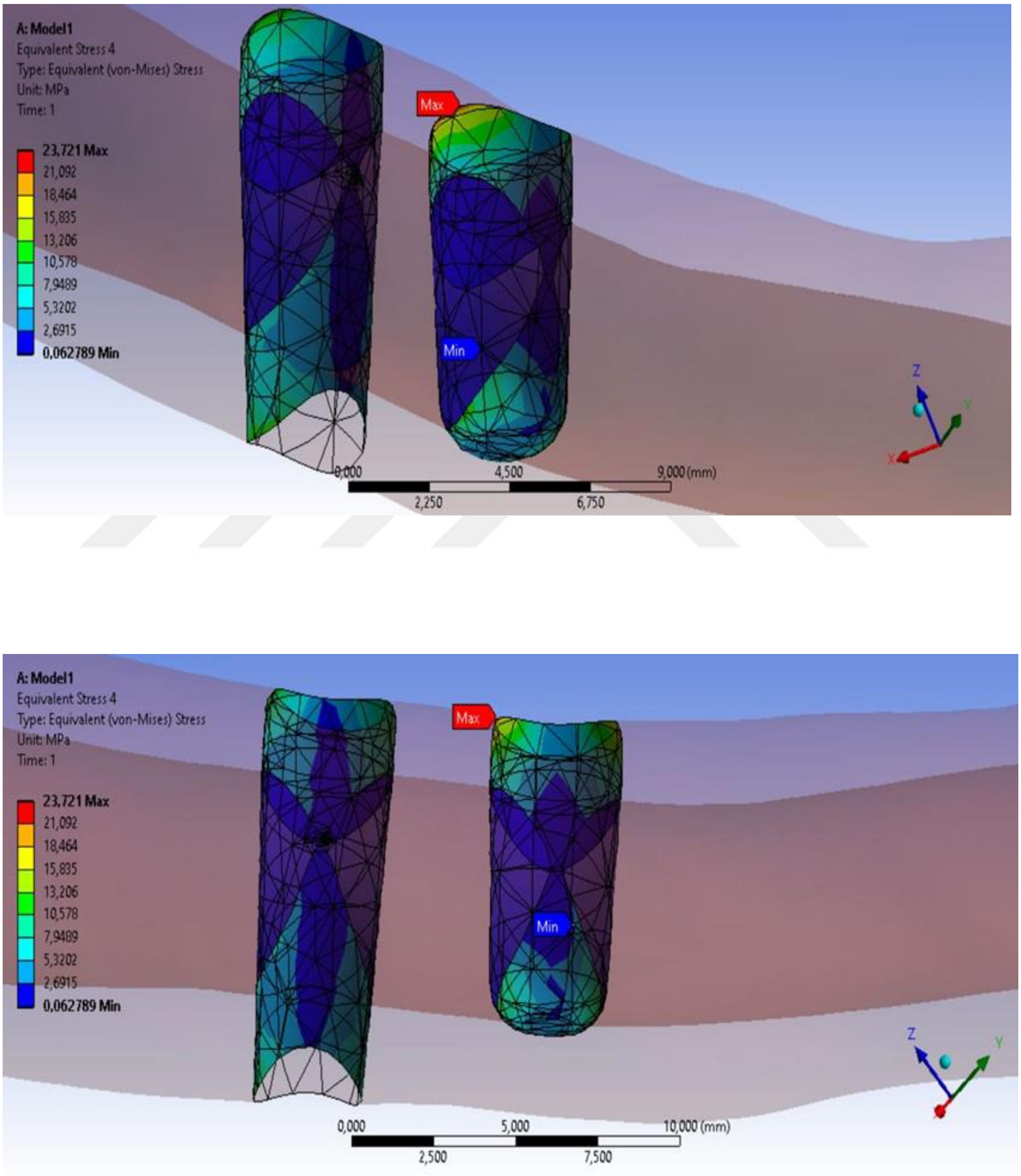


Figure 4.2. Equivalent (Von Mises) stress in the bone around the implants.

Total Deformation was measured as 0.1249 mm in the area of the junction of the mandible with the fibula, around the step and in the section extending to its distal.

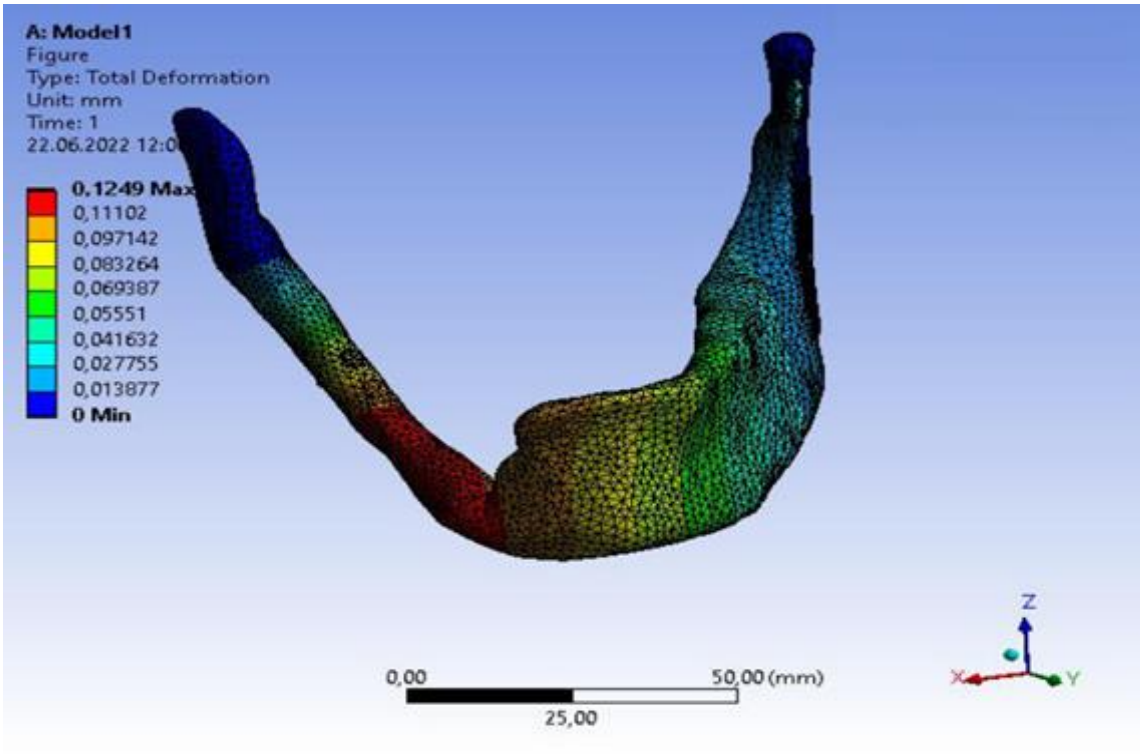


Figure 4.3. Total Deformation values in the two implant placed model.

The highest stress and deformation data in the model are shown in (Table 4.1), and the values are shown with bar graphs for comparison (Figure 4.4).

Table 4.1: Highest Von Mises stress, and Total Deformation data in the model.

	Higest Von Mises stress (MPa)	The bone around the implants Von Mises stress (MPa)	Total Deformation (mm)
3mm gap, two implant Monocortically, and bicortically placed.	61,544	23,721 14,450	0,1249

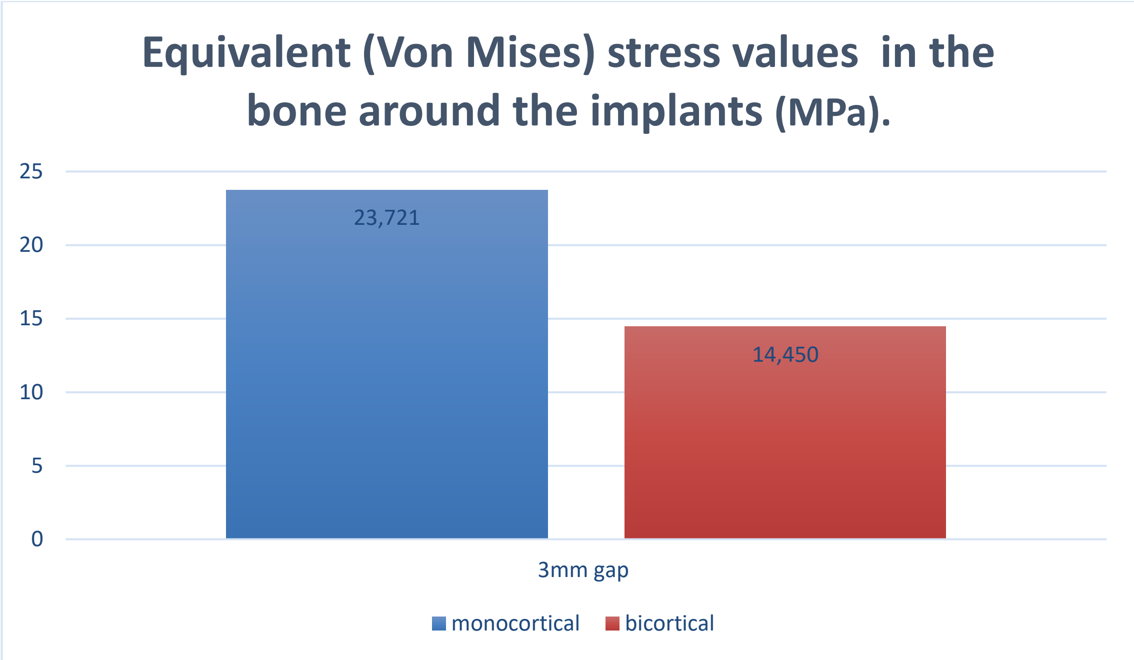


Figure 4.4. Bar graphic of monocortically and bicortically placed implants.

4.2. Model 2 Evaluation

Three implants are placed to model monocortically and bicortically at 3 mm, 7 mm, 10 mm intervals. A total of 120N force is applied to the three implants placed in the model. Von Mises Stress and Total Deformation values, which are caused by the application of 120N vertical force were determined and shown in (Figure 4.5), (Figure 4.6), and (Figure 4.7). In the model, the highest Von Mises stress was observed as 52,638 MPa in the superiodistal position at the junction of the fibula and the ramus region of the mandible, in the bicortical location modification with a 10 mm interval.

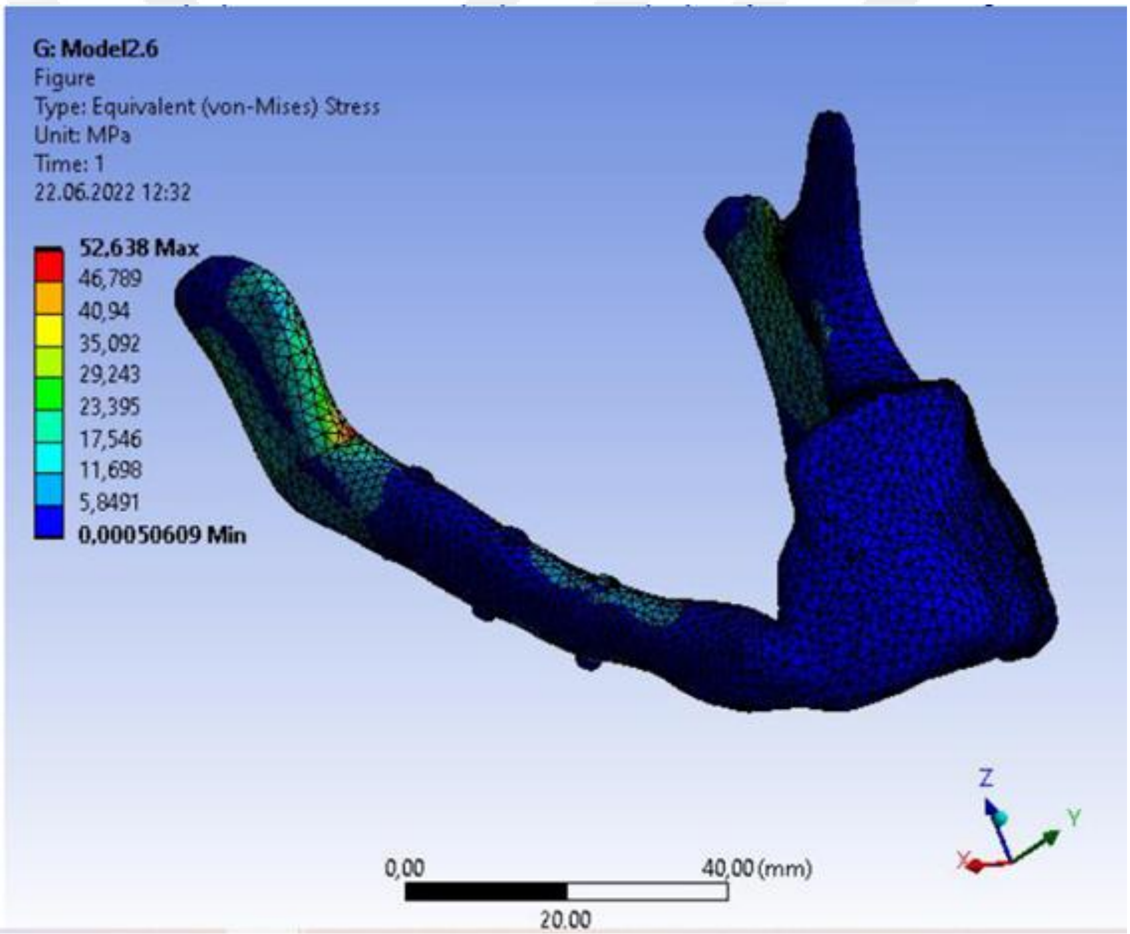


Figure 4.5. Equivalent (Von Mises) stress in the bicortical location modification with a 10 mm interval.

The highest Von Mises stress in the bone around the implant was measured in the monocortical location modification with a 10 mm interval as 19,238 MPa in the cortical bone of the fibula, in the most medially placed implant's superiomesial portion.

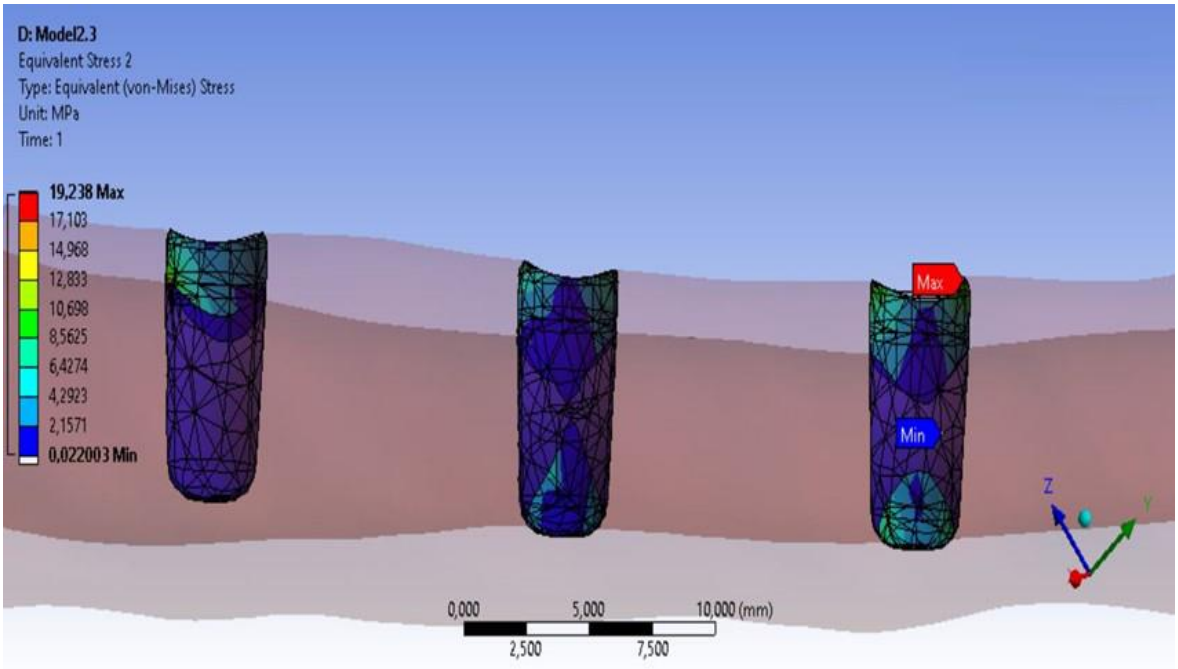


Figure 4.6. Equivalent (Von Mises) stress values in the bone around the implants monocortical location modification with a 10 mm interval.

The highest Total Deformation was measured as 0.1010 mm in the monocortical modification model, which was arranged at 10 mm intervals in the area extending to the step circumference and distal at the junction of the mandible with the fibula.

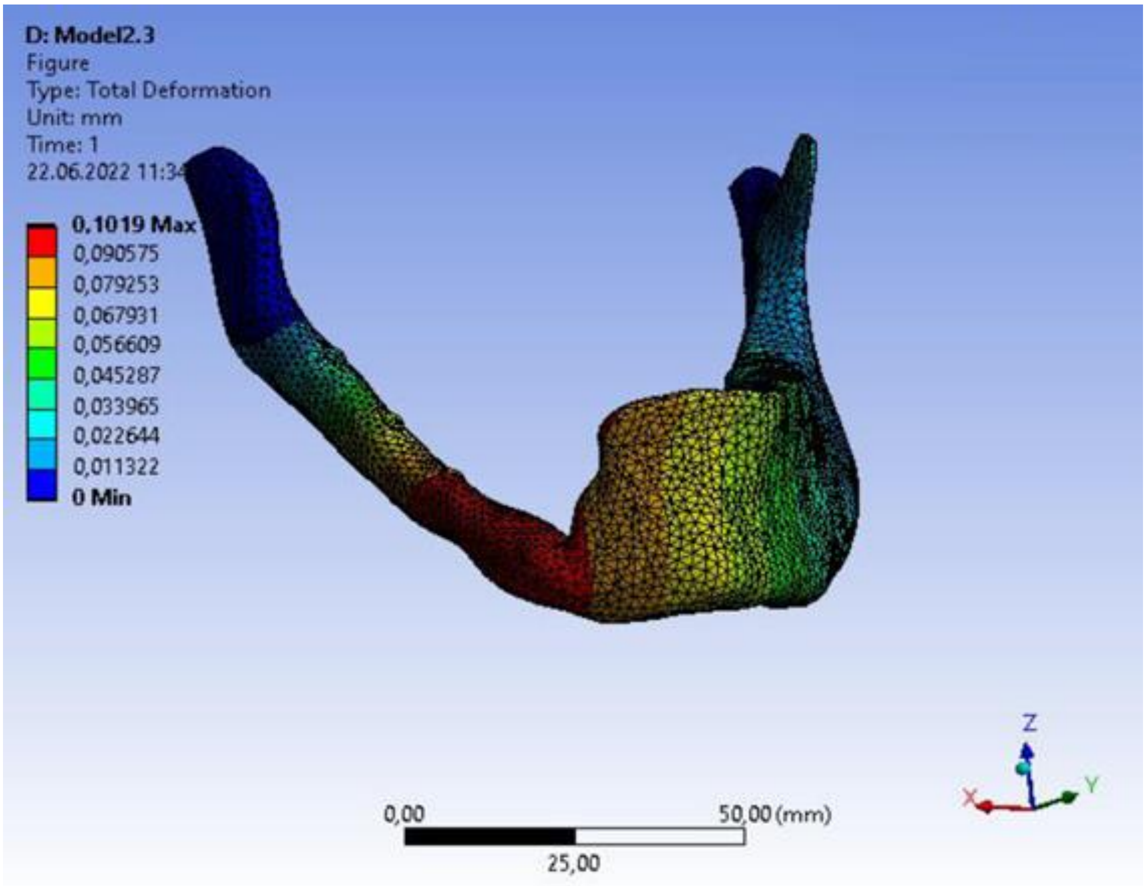


Figure 4.7. Total Deformation values in the 10 mm intervals monocortical model.

The highest Von Mises Stress and Total Deformation data in the model are shown in (Table 4.2), and the values are shown with bar graphs for comparison (Figure 4.8), and (Figure 4.9) and (Figure 4.10).

Table 4.2. Highest Von Mises stress, and Total Deformation data in the model 2 and all its modifications.

	Von Mises Stress values (MPa)	Von Mises values (MPa) in bone around the implant	Total Deformation (mm)
3 implant, 3mm gap, monocortical	47,954	17,651	0,0729
3 implant, 7mm gap, monocortical	50,864	18,717	0,0876
3 implant ,10mm gap, monocortical	52,313	19,238	0,1019
3 implant,3mm gap, bicortical	47,275	13,061	0,0728
3 implant,7mm gap, bicortical	49,851	17,176	0,0868
3 implant,10mm gap, bicortical	52,638	18,268	0,1005

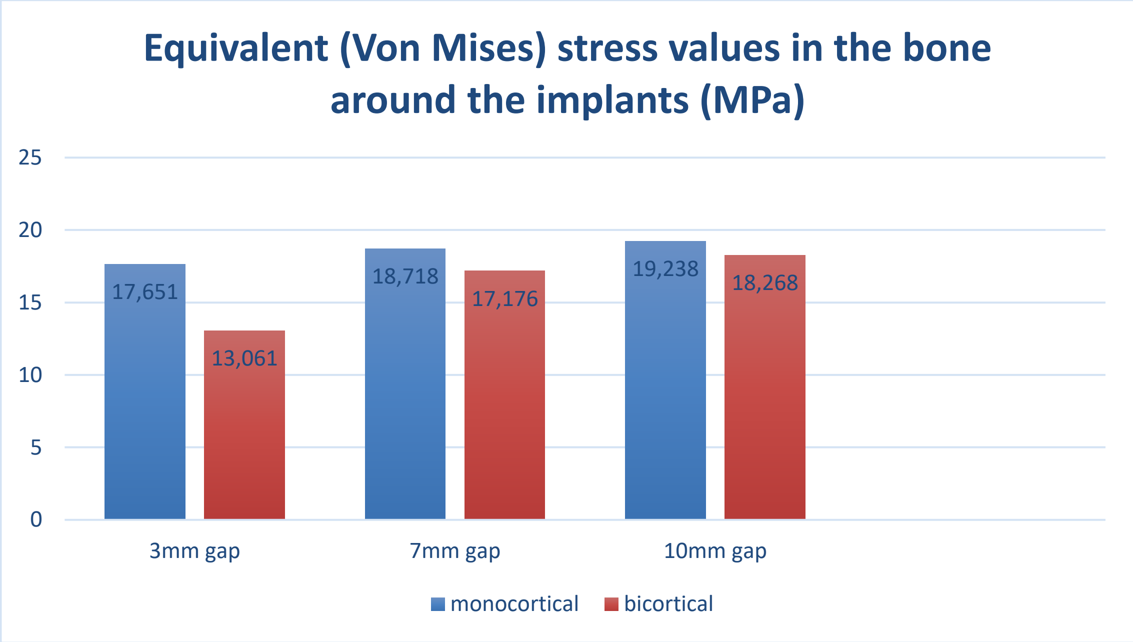


Figure 4.8. Bar graphic of highest Von Mises Stress values of bones around the implants.

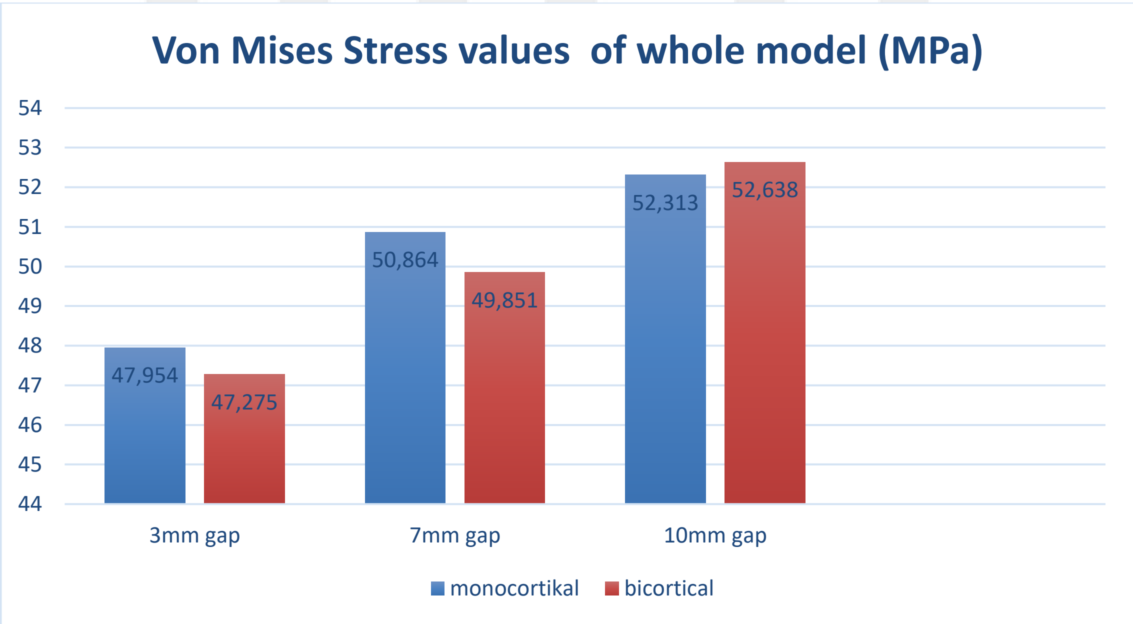


Figure 4.9. Bar graphic of highest Von Mises Stress values of the models.

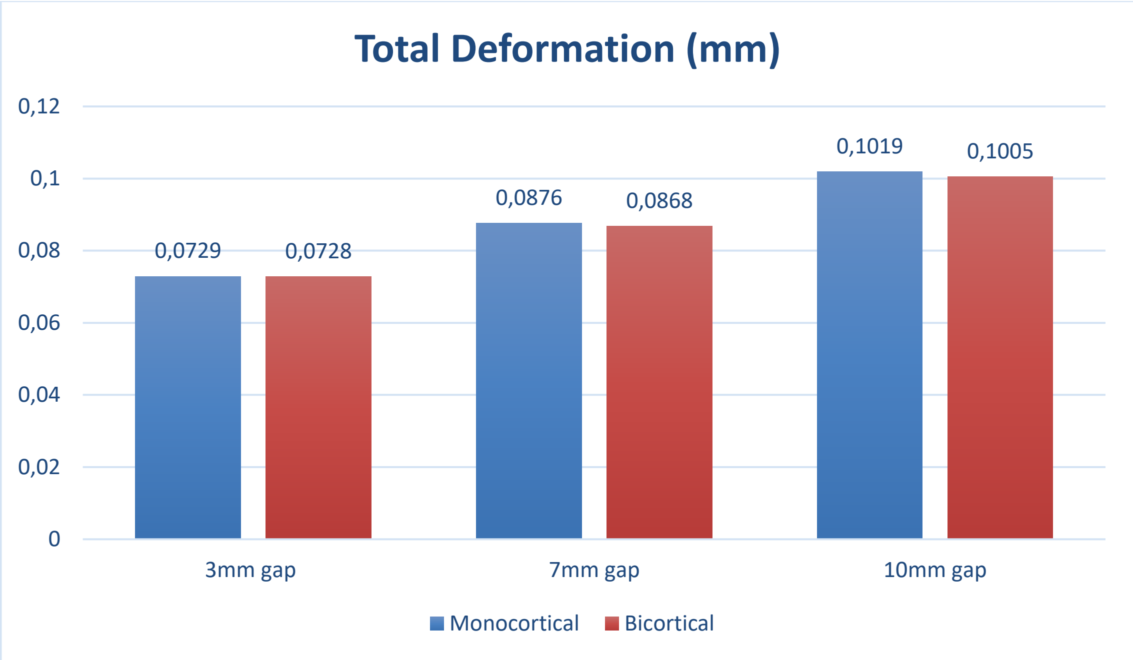


Figure 4.10. Bar graphic of Total Deformation datas of the models.

4.3. Model 3 Evaluation

Monocortical and bicortical placement of an implant with a distance of 3 mm, 7 mm, 10 mm to the step was investigated. 120N force is applied to the implant that placed in the model. Von Mises Stress and Total Deformation values, which are caused by the application of 120N vertical force were determined and shown in (Figure 4.11), (Figure 4.12), and (Figure 4.13).

In the model, the highest Von Mises stress was observed as 142.05 MPa in the unresected side of the condyle neck in the monocortical placement modification with the 3 mm pitch proximity.

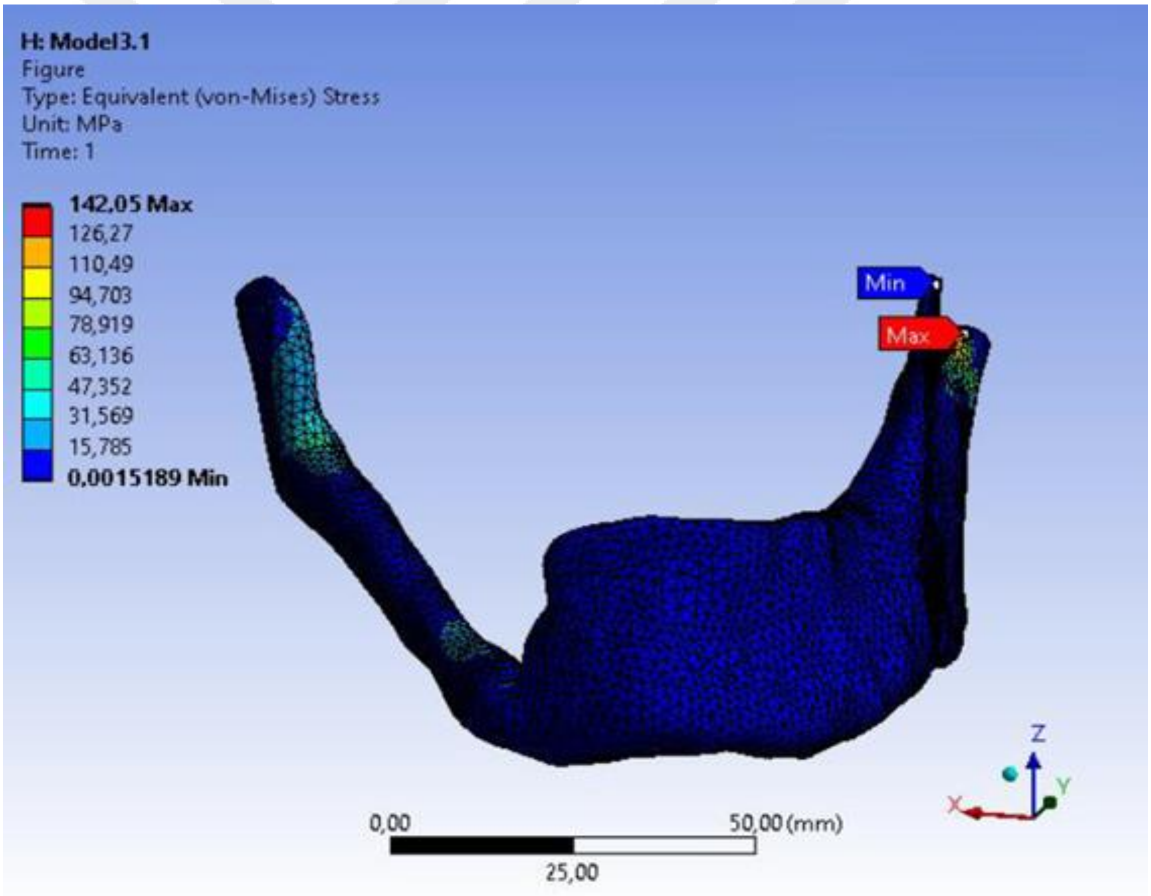


Figure 4.11. Equivalent (Von Mises) stress values in the monocortical location of an implant 3 mm to step.

The highest Von Mises stress value in the bone around the implant was measured as 64,373 MPa in the inferior and mesial part of the cortical bone of the fibula in the bicortical and 10 mm distance modification to the step.

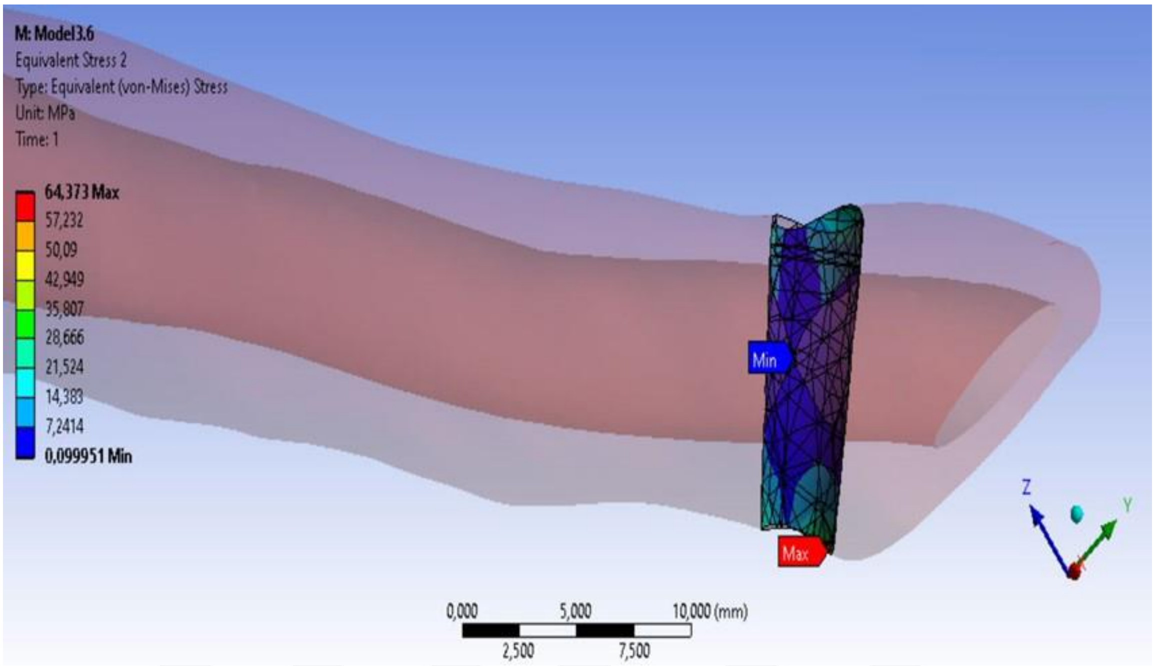


Figure 4.12. Equivalent (Von Mises) stress values in the bicortical location of an implant 10mm to step.

The highest Total Deformation value was observed in the model implant placed as monocortical at 3 mm distance from the step. Total deformation was observed in the inferior junction of the fibula and the mandible.

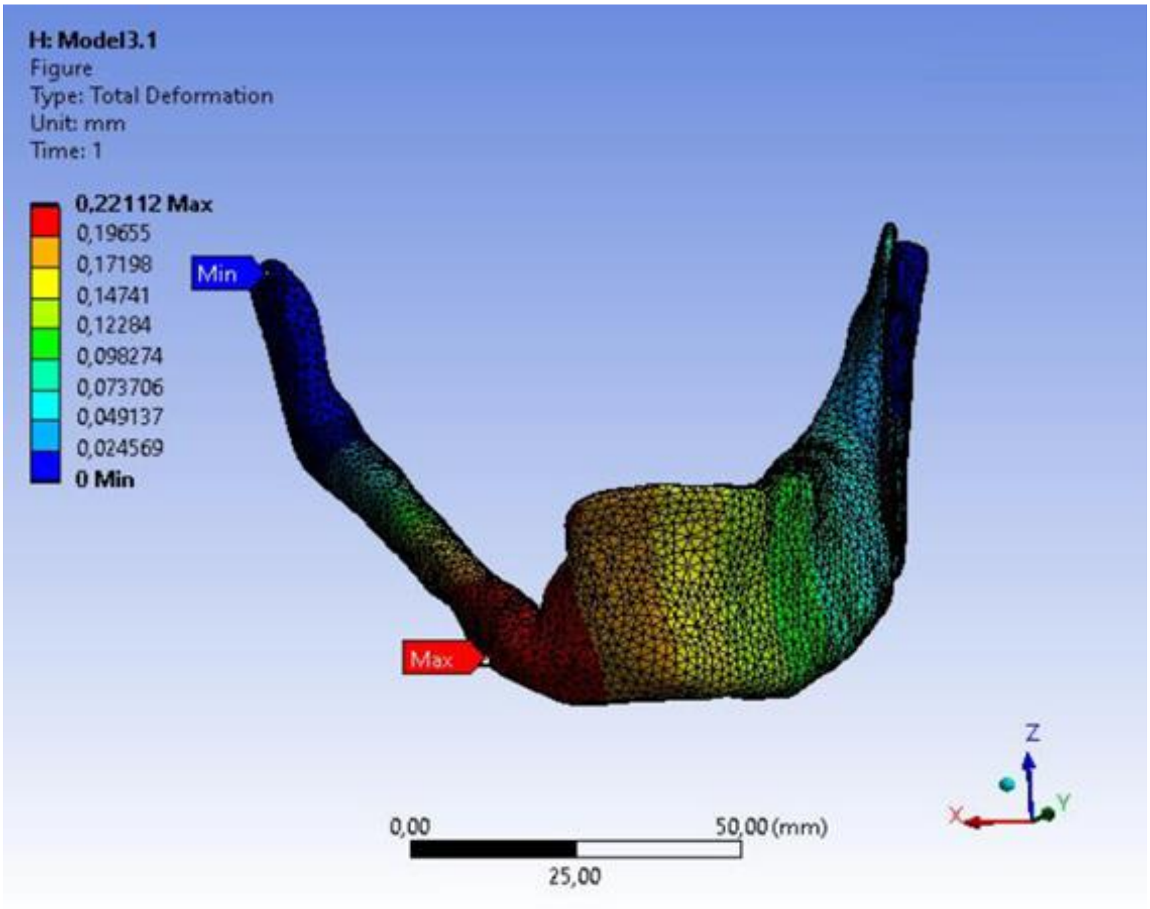


Figure 4.13. Total Deformation values in the 3 mm to step monocortically placed implant model.

The highest Von Mises Stress and Total Deformation data in the model are shown in (Table 4.3), and the values are shown with bar graphs for comparison (Figure 4.14), and (Figure 4.15) and (Figure 4.16).

Table 4.3. The Highest Von Mises stress and Total Deformation assessments in the model 3, and all its modifications.

	Von Mises Stress values (MPa)	Von Mises values (MPa) in bone around the implant	Total Deformation (mm)
3mm to the step, monocortical	142,05	18,696	0,2211
7mm to the step, monocortical	126,28	38,722	0,2158
10mm to the step, monocortical	119,56	42,86	0,2100
3mm to the step, bicortical	134,45	21,196	0,2209
7mm to the step, bicortical	131,45	50,927	0,2157
10mm to the step, bicortical	118,59	64,373	0,2067

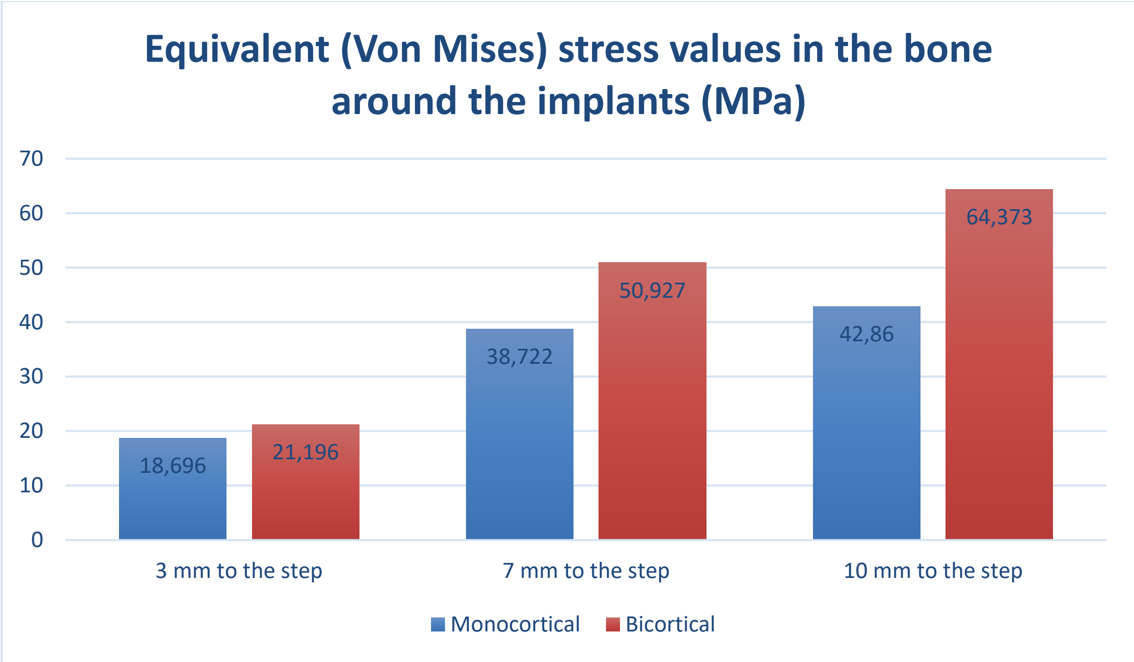


Figure 4.14. Bar graphic of highest Von Mises Stress values of bones around the implants.

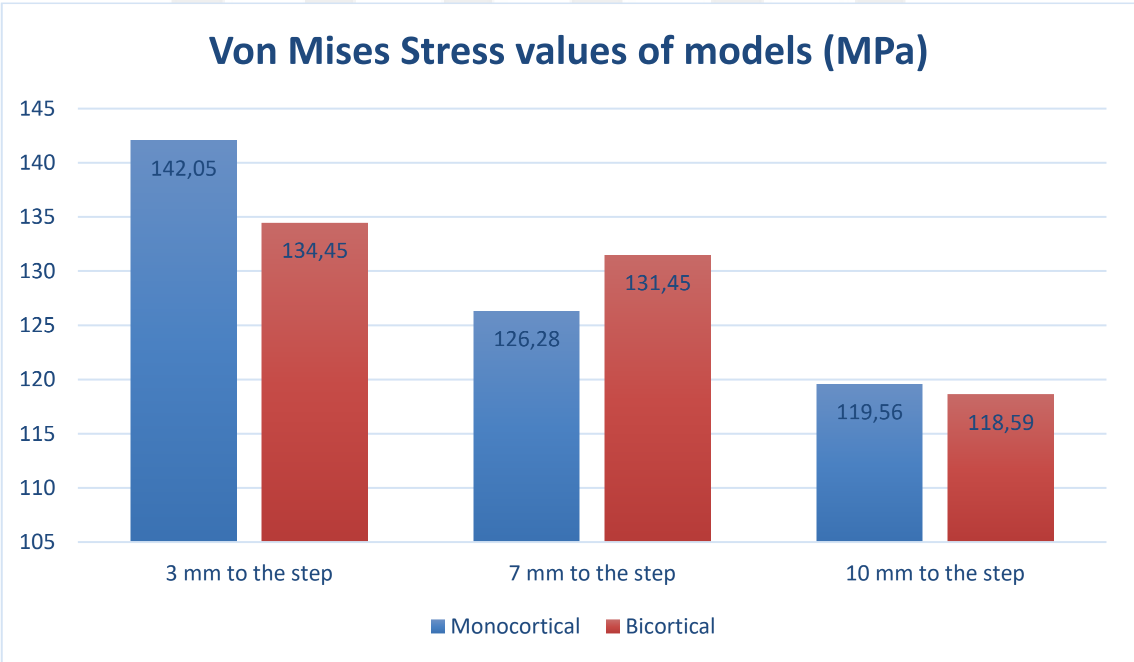


Figure 4.15. Bar graphic of highest Von Mises Stress values of the models.

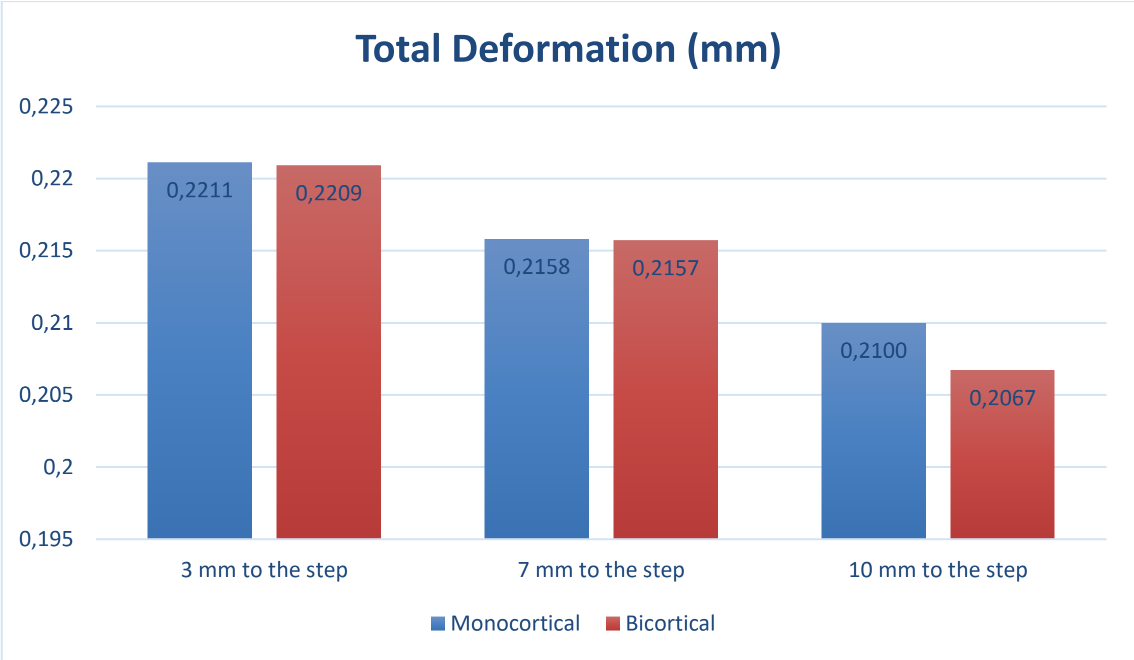


Figure 4.16. Bar graphic of the highest Total Deformation datas of the models.

4.4. Model 4 Evaluation

Monocortical and bicortical placement of three implants with 10 mm apart each other, and 0.5 mm, 2 mm, 1 mm from the edge of the fibula was investigated. 120N total force is applied to the implants that placed in the models. Von Mises Stress and Total Deformation values, which are caused by the application of force were determined and shown in (Figure 4.17), (Figure 4.18), and (Figure 4.19).

The highest Von Mises stress value in the bone around the implant was measured as 31,590 MPa in the cortical bone of the fibula, in the superiodistal area of the most distally positioned implant.

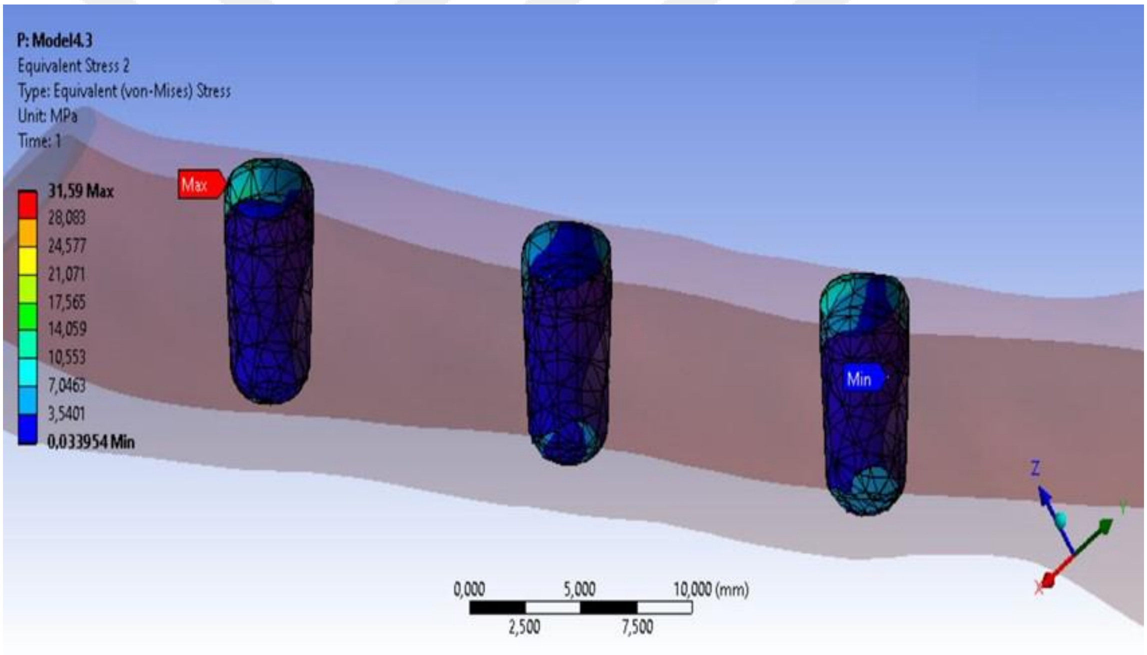


Figure 4.17. Equivalent (Von Mises) stress values of the bone around the implants that monocortically and 1 mm close to the edge.

When the general Von Mises stress was evaluated in the model, a stress value of 52,923 MPa was observed in the superior region of the fibula and the mandible junction which the implants were 2 mm close to the edge and monocortically placed modification.

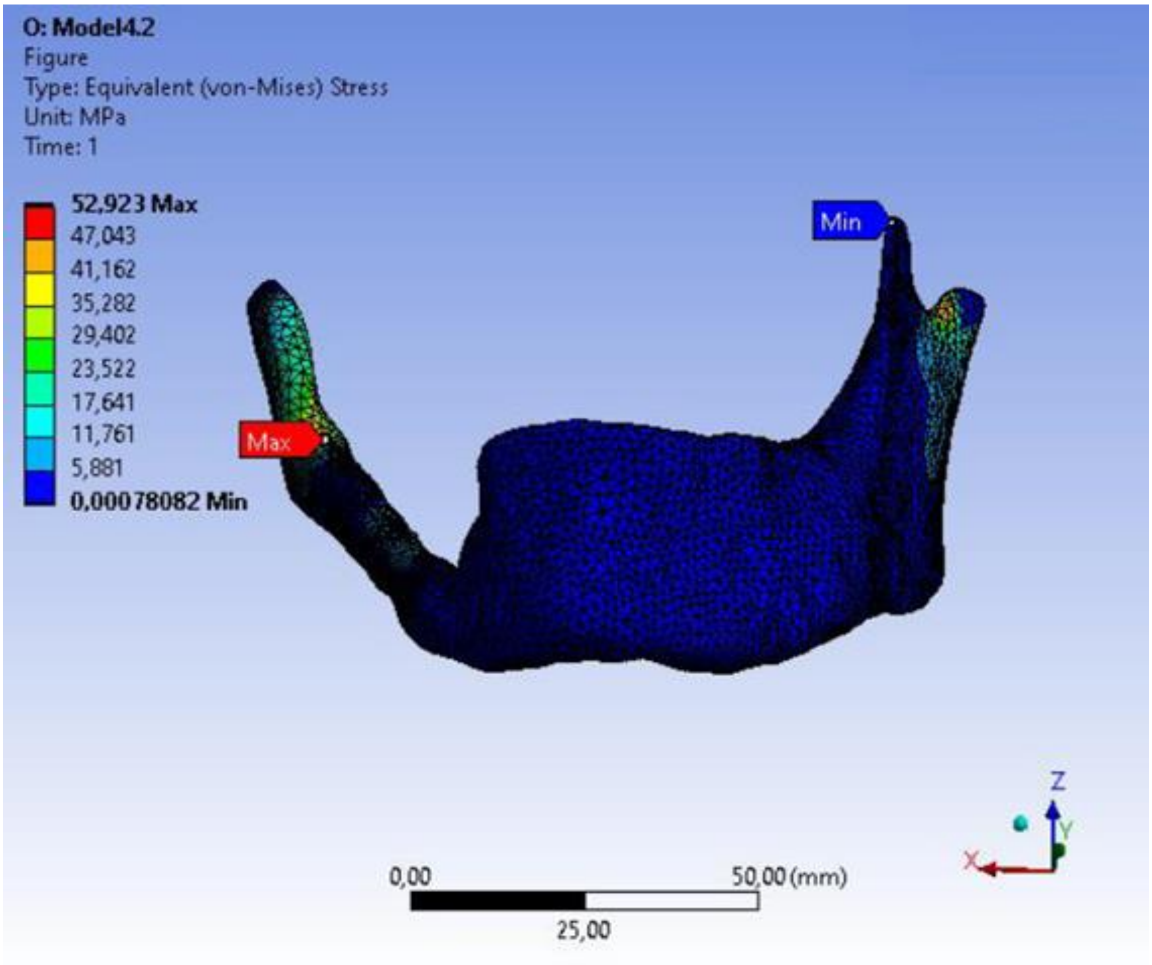


Figure 4.18. Equivalent (Von Mises) stress values of the bone around the implants 2 mm close to edge and monocortically placed implant model.

The maximum Total Deformation was observed as 0.1034 mm in the anterior junction of the fibula and the mandible in the modification, which was positioned close to the edge of 0.5 mm.

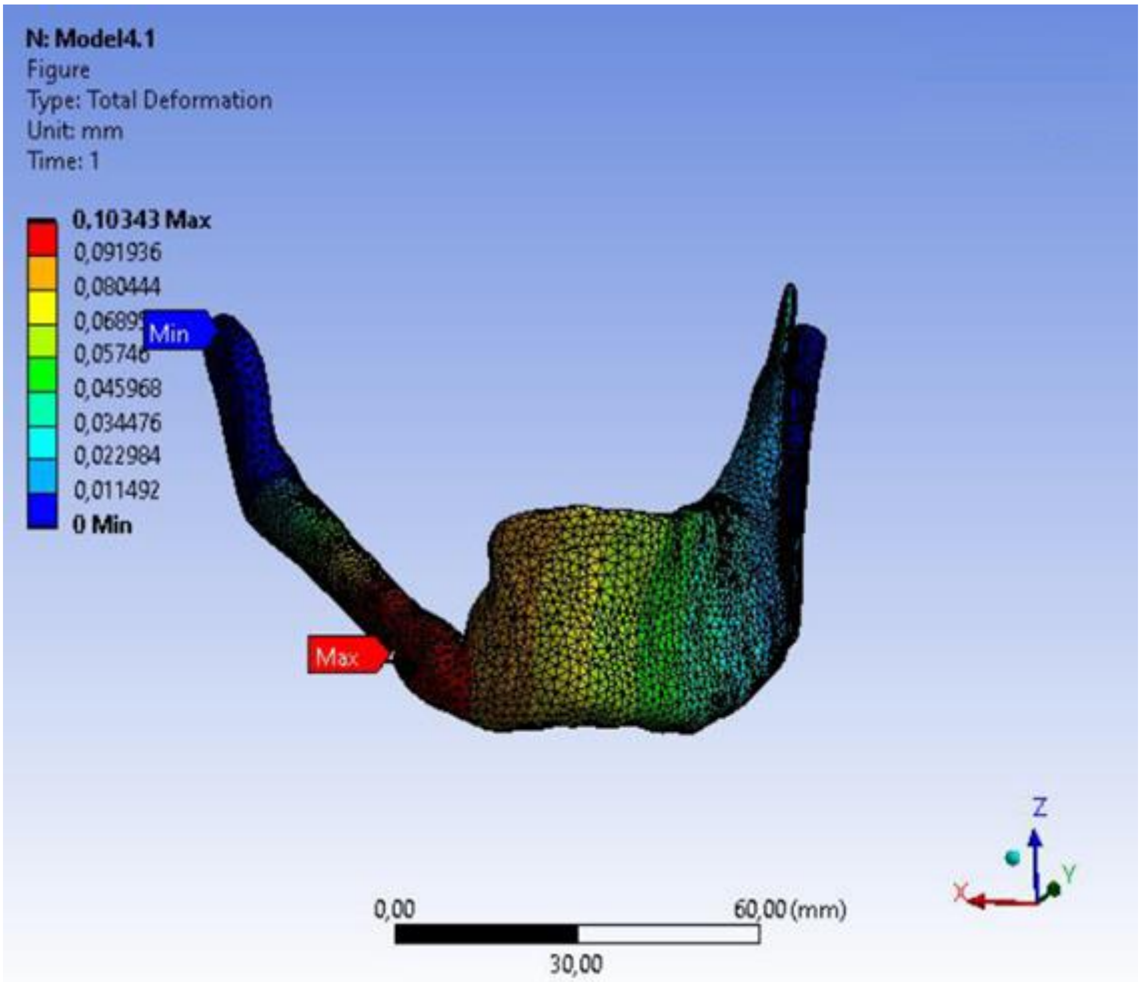


Figure 4.19. Total Deformation values in the 0.5 mm close to edge and monocortically placed implant model.

The highest Von Mises Stress, and Total Deformation data in the model are shown in (Table 4.4), and the values are shown with bar graphs for comparison (Figure 4.20), and (Figure 4.21) and (Figure 4.22).

Table 4.4. The highest Stress values of models that monocortical and bicortical placement of 3 implants 10 mm apart from each other, and 0.5 mm, 1 mm, 2 mm from the edge of the fibula.

	Von Mises Stress values (MPa)	Von Mises Stress values (MPa) in the bone around the implants	Total Deformation (mm)
0.5mm close to edge, monocortical	52,855	15,748	0,1034
1mm close to edge, monocortical	52,774	31,590	0,1027
2mm close to edge, monocortical	52,923	17,930	0,1019
0.5mm close to edge, bicortical	52,577	16,200	0,1024
1mm close to edge, bicortical	52,489	17,348	0,1018
2mm close to edge, bicortical	52,548	17,320	0,1006

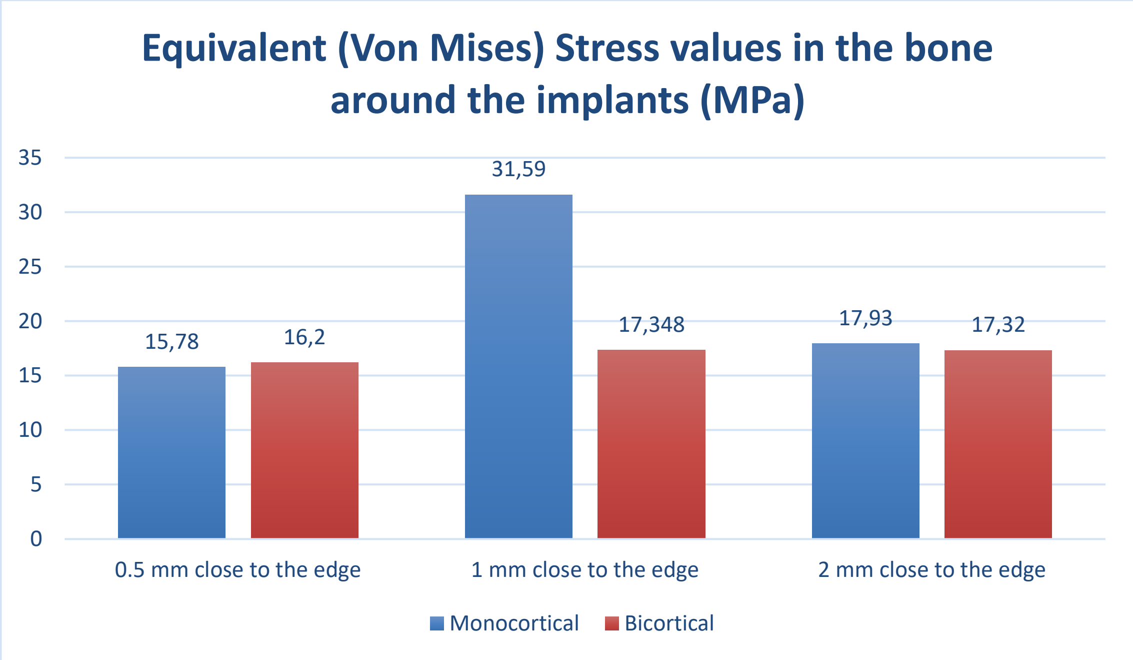


Figure 4.20. Bar graphic of highest Von Mises Stress values of bones around the implants.

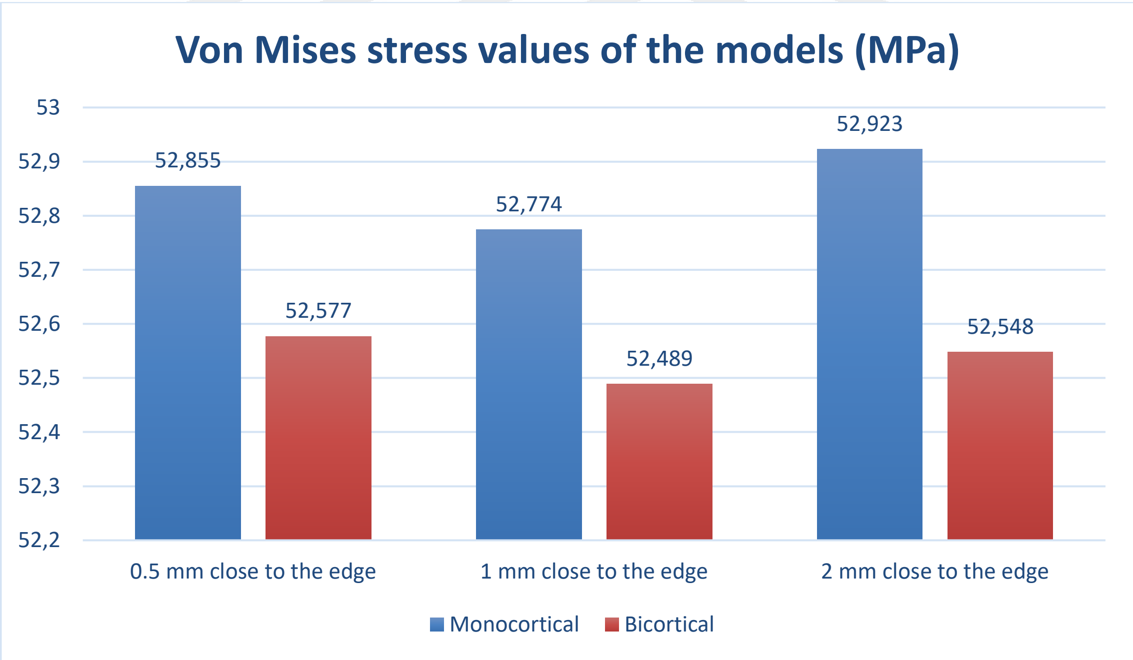


Figure 4.21. Bar graphic of highest Von Mises Stress values of the models.

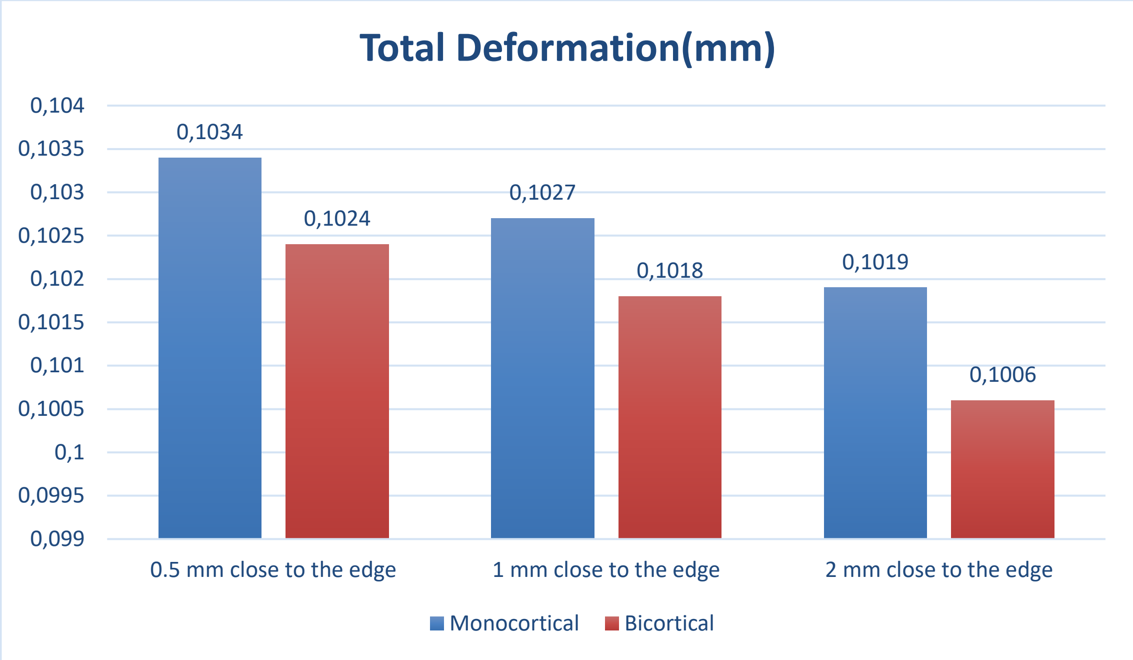


Figure 4.22. Bar graphic of the highest Total Deformation datas of the models.

5. DISCUSSION and CONCLUSION

In the present study, the Von Mises stresses of the implants placed in the fibula in different numbers and locations as monocortical and bicortical, under 120N force, and the Total Deformation values of the models evaluated by the finite element analysis (FEA) method. The most suitable position, and combination values for implant rehabilitation for fibula flap in jaws were assessed.

Resections for the handling of oromandibular cancer, bisphosphonate- involved osteonecrosis, osteomyelitis, and infection may outcome orofacial disturbance and functional disorganizations of the masticatory system (105). The recruitment of patients with continuity defects of the jaws after tumor ablation is still vastly challenging. Resection can lead to important facial deformity, altered oral function, and commitment psychological problems. As mentioned in literature complex defects need not only cosmetic restoration but also functional reconstruction in order to allow patients to regain their family, social, and professional life under optimum circumstances, and as soon as possible. The reconstruction of the anatomical continuity with revascularized free flaps is tremendously important for the reconstruction of facial contour and jaw duty (106,107,108).

Formerly, after the maxillomandibular reconstructions patients were left without dentition or were rehabilitated with removable dentures. The development of dental implants proposed a major beneficiation to the restoration of enough function. Endosseous implants have turned out to be a very popular choice among partially and fully edentulous patients to regain dental performance as well as to get an aesthetic appearance. As a result of the huge clinical success the demand for these artificial surgical components is increasing day by day (5,109,110,111).

The use of fibula flaps for the restoration of maxillofacial defects does not have a very old history. Because of its bone quality, cortical stoutness, and possibility to make osteotomy and adapt to the jaw, it is a perfect graft for maxillomandibular reconstruction in jaw defects and insertion of dental implants. The fibula free flaps have a high survival rate of 94.9%, in addition, it has a 98.6% implant success and 93.1% survival rates of implants (8). For Roumanas, survival rate of implants in the fibula is 94.6% (112). Teoh et al. (2005) statemented the survival rates of implants in fibula 97.0%, 97.0%, and 79.9% at 1, 5, and 10-year follow up respectively (113).

Fibular bone grafts and implant positioning affects implant osseointegration and the probabilities of dental rehabilitation. Stress dispersion around endosseous dental implants is significant element defining treatment achievement. Owing to the inimitable histomorphologic characteristic of the fibula bone, the implant operating way in fibula is dissimilar from the native maxilla or mandible (114).

Evidence about optimum implant positioning and protocol in the fibula free flaps is not sufficient. Dental implantology in fibula bone has a restricted knowledge about favorable size, and convenient space from the adjacent implant and remaining tooth.

Biomechanics are significant for bony regeneration and survival of implants in functional maxillary and mandibular reconstruction. The biological response of bones and accrued implant positioning affect implant longevity. Micromotion of the implant fixture and extreme stress at the implant-bone surfaces have been proposed as potential causes of bone loss and failure (115). The main significant agents determining peri-implant tissue health are the stress quantity and stress accumulation at the around the bone of the implant (116,117). The dispersion of stresses in peri-implant bone has been researched by FEA in a few studies (118,119). However, there is a limited study that has included on analysis of biomechanics to guide the optimal position of implants for fibular graft and limited knowledge about fibula bone and implant stress distribution (51).

In light of this information, the stress and effects of dental implants on the bone are the starting point of our study. In the current publications, there is no FEA study in which implants were placed and evaluated in different numbers, positions, different distances to the fibula margins and mandibular binding margins. The present study aims to assess the Von Mises stress distribution and Total deformation under 120N vertical load on different modified fibula reconstructed mandibular models with different implant location modificated situations with the FEA method. To reach appropriate and accurate stress distribution, both the whole fibula, implant-bone interface surface, and fibula-mandibula binding area were assessed.

The finite element analysis method is used to examine the change of a certain part of the object with the desired force. Analysis of mathematical models that represent certain basic properties of real objects (120). With the FEA method, the structure can be examined in 2 or 3 dimensions. 2D analysis methods are not variable, so their research on dynamic problems is limited. Since the oral, morphological, and prosthetic features of the patient cannot be fully reflected, the clinical conditions cannot be given exactly. However, in the models investigated in 3D, the force can be examined mathematically, and the force transmission and distribution can be accurately reflected in the model (121).

The advantages of finite element stress analysis over other stress analyses are as follows: Finite element stress analysis is a simpler and more effective method. The model can be prepared very close to the real state of the object and the results can be repeated on the computer since the mathematical model is virtual. The parameters, geometry, and test conditions of the model can be changed easily. Results are taken in a shorter time. More specific loadings such as lateral and oblique can be made, and the stress distributions obtained in the analysis results are very close to the truth (122,123,124). Compared with other force analysis methods such as the photoelastic stress analysis method, and strain gauge stress analysis method, the FEA method can simulate bone and surrounding tissue structures very closely, examine the stress transmission and distribution mechanism in implant and surrounding tissues in more detail, and provide versatility. For this reason, it was preferred as the analysis method in the study.

In all in vitro analysis studies, it is not possible to reproduce the exact same properties of in vivo structures. In FEA studies, unlike biological structures, all elements are considered homogeneous, isotropic and linear. Papavasiliou et al. (1996) reported that the grade of osseointegration had not influenced the stress levels or stress distributions for axial loads and oblique loads in finite element analysis (125). Although 100% osseointegration is not possible biologically, in our study, the osseointegration between implant and bone was accepted as 100%, taking into account other studies (92,122,126). In finite element stress analysis studies, computerized tomography is used to obtain the bone image in a similar shape and size to the original (127). Images created by computed tomography are converted into a 3D detailed virtual model of the jaw. This virtual model gives a realistic idea of anatomical bone morphology in addition this cortical and trabecular bone properties can be obtained similarly (128,129). In the study, the mandible of a patient who underwent hemi-mandibular resection, and was reconstructed with a fibula free flap was imaged in DICOM format with 1 mm cross-section CT and a model was created. The 3D model was turned into a smooth surface with proper proportions with Geomagic 3D software, and the modeling was completed.

In the case of maxillary or mandibular functional reconstruction with placement of dental implants, extensive stresses are expected during mastication but, bite and chewing forces will be reduced postoperatively (130). After resection and reconstruction of jaws, the masticatory force is reduced and the masticatory cycle is slower (131,132). According to Anne-Gaëlle, B et al. (2011) all the resection and reconstruction operations have an effect on mastication biomechanics. A decrease in the masticatory force, and limited mandibular movements are the consequences (48). Y Ken et al. (2015) interpret bone stress near an implant placed at the margin between the mandible fibular flap in mandibular reconstruction, and they applied 100N vertical force to evaluate Von Mises stress distribution (133). Furthermore, masticatory load working on the molar region was reported 75-300N (134). Haraldson and Carlsson gaged biting forces of 19 patients, 15,7N for gentle biting, 50N for biting as chewing, and 144,4N for maximum biting who had been treated with implants for 3.5 years (135). Other researchers carried out the masticatory forces between 17-300N (average 111N) measured with the prosthodontic treatment of patients with vascularized bone grafts (136). Static force measurements explain the average biting force is 100-150N in adult males, and males have higher biting force than females. They also reported 10,2 - 57,5 N biting force on those who had been treated with an implant-supported prosthesis (137). According to the information, the 120N force was chosen that applied to the implants vertically in the present study.

The structures to be examined in finite element stress analysis are divided into geometric shapes called elements, and these parts are connected at nodes. The amount of change that occurs at the nodes under stress determines the analysis. Using as many elements as possible is important for a more precise determination of the force distribution. The number of elements and nodes used in the creation of the mathematical model is important. The higher the number, the more detailed and realistic results are achieved (19). In addition, the Elasticity modulus and Poisson ratios of the materials that make up the structure are processed to create conditions similar to the natural reactions of the structures (21, 138). Thiyaneswaren N et al. (2014) stresses around implants fitted in normal and fibula reconstructed mandibular models using FEA were studied with 6000 nodes and 30000 elements (139). Young-Seok P et al. (2013). In the study in which the implant-supported crown in the fibula was examined with 38.570 nodes and 80.189 elements (102). Peng Li et al. (2013) used 56.990 nodes and 32.197 elements in their study (140). When the number of nodes and elements of the studies in which jaws reconstructed with fibula free flap or implant-placed fibula was evaluated with FEA, the number of nodes and elements in our study is 100,000 nodes and 60.000 elements enough to give precise and sufficient results.

Also, in our finite element stress analysis study, the Elastic modulus and Poisson ratio values of the mandible cortical bone, mandible trabecular bone, fibula cortical bone, fibula trabecular bone and titanium(Ti-6Al-4V) implant were determined by considering the values most commonly used in the studies and are shown in table 3.1 (141,142,143).

Von Misses stress values in our study were evaluated separately both in the whole model and in the bone around the implants. The total deformation data is the flexure data in mm in the model as a result of stress, which is considered in the full model. The highest von Mises stress values in our study: When the overall model is evaluated, it is the data of 142.05 MPa in the model which created with 1 implant 3 mm away from the step. This stress was observed on the contralateral side in the area extending from the condyle and anterior of the condyle neck to the sigmoid noch. Followed by 126.27 Mpa at the posterior junction of the graft with the mandible. It was examined that the stress data in the models decreased as moved away from the steps. In addition, stress reduction was observed as the number of implants increased.

The maximum Von Mises value in the bone around the implant was observed as 64,373 MPa in the implant model placed 2 mm away from the graft-bone binding area. This stress was analized at the apex of the implant we placed bicortically. In other models, stress concentrations observed in the neck region of the implants, while observed stress where it penetrates the graft-bone junction. In the light of this information, the study indicaded that the Von Misess values are high in implants placed close to the fibula-mandible junction. When the total deformation data is evaluated, we see the highest value as 0.22112 mm in the implant model, which is placed 3 mm close to the step. Deformation values are concentrated in the anterior binding region affecting the implant and surrounding fibula and mandible. As the number of implants increases and the distance from the step increases, the values decrease in the positive direction.

The implant survival rate of fibula free flap after jaw reconstruction is known to be considerable and announced to about 85% to 98,9% (29,144). It was already declared that cortical bone thickness is important. The cortical bone supports the implant is an important factor in osseointegration including the initial stability (145).

Cortical bone strength range from 170-190 Mpa under compression trabecular bone strength range from 2-5 Mpa under compression. Stresses much more than these evaluations may create bone structure deformation (141,142). Even though, there is no constant linear correlation between stress and bone failure, the stress degree required for instantaneous fracture of bone was declared to be 120 Mpa (143). As the occlusal forces first pass from the implant to the cortical bone, only a small amount is transmitted to the apical bone. The Stresses are mostly concentrated in the neck area of the implants in the cortical bone (146,147). Sevimay et al. (2005) evaluated the amount and distribution of stress created by implants in bones of different quality by applying 150N vertical force in FEA studies, and reported that the stresses intensified in the neck of the implant in all bones (127). Thiyaneswaren N et al. (2014) reported that in their study the Von Misses stress consisting of the cervical bone zone the cervical area of implants (139).

The fibula was informed to have a quite thick cortical bone of about 2,5 - 3,5 mm (148). The fibula has a bicortical structure, and a great rate of success can be obtained by the bicortical settlement of the implants that lets a major bone-implant contact surface (130). The utilization of cortical bone is significant to obtain implant stability. Mostly monocortical fixation is performed in which the penetration of the cortical bone occurs only near the implant collar. According to studies, bicortical fixation displays decrease in bone stress (149,150,151).

Wu, J. C. H. et al. (2012) examined the biomechanical effects of varied lengths of implants in mandibular and fibular bone. 125 N was exerted to the suprastructure at a 45-degree angle relative to the long axis of the implant, and maximum von Mises equivalent stresses, stress distribution were evaluated. In the mandible, with the 6 mm, 10 mm, and 15 mm implants, the stresses were in the order of 115.636 MPa, 155.943 MPa, and 157.105 MPa. The mean stresses were 64.145 MPa, 77.925 MPa, and 78.500 MPa, respectively. In the fibula, the maximum stresses were 174.04 MPa, 157.456 MPa, and

144.353 MPa with in the order of the 6 mm, 10 mm, and 15 mm implants. In the fibula models, the micromotion was lower than in the mandible models. Von Mises stress in the fibula was distinct from that in the mandible. They put into words that short implants may be a choice for oral implantation in the mandible; but, implants in the fibula should likely have bicortical anchorage (149). Huang H et al. (2009) using FEA, reported bicortical settlement diminished the top stress in cortical and cancellous bone (152). Young-Seok P et al. (2013) performed a study on only an implant with a 4.0 mm diameter and a length of 10 mm in the implant-supported crown-placed mandible and fibula models, in which they evaluated biomechanic values with FEA. 50N and 150N vertically, 50N obliquely applied separately. The maximum Von Mises stress data were assessed much more in the mandible model than in the fibula model due to bicortical insertion diminishing the stress in the fibula bone. In addition, higher stress concentrations consisted of cortical bones in both models. Oblique load overall stress distribution was similar in the two models. But, they were distinct from and higher than those with perpendicular loadings. The enhancement of vertical load consistency from 50N to 150N did not generate remarkable segregation. The thick cortical sheet of the fibula is thought to be the reason for the favorable consequences in the fibula model (102). Holberg et al. (2014) announced that stress was importantly lower in bicortical positioning than monocortical positioning (153). Furthermore, other studies declared a decrease in stress data at the cortical bone near the upper base by the deep insertion of the implant and using a longer implant (154, 155). In the present study, Von Misses stresses were observed in the neck of the bone around the implant, except for the implants placed close to the junction surface of the fibula graft and the mandible and penetrating the junction surface. Also, which observed a decrease in stress values between bicortical and monocortical locations, the study obtained data showing that stress decreased as a result of bicortical location.

The fibula is a bone that has 18-25 mm length, 10- 15 mm height, and 8-9 mm wide. According to the preceding analysis, the range of implant diameter 3,75 - 4,8 mm is convenient for insertion in a reconstruction mandible with a fibula flap (156,157). The enactment of functional forces causes stresses and strains within the implant-bone and implant-prosthesis complex, which also influence the bone remodeling around the implants (158). Still, the physiologic tolerance thresholds of human jawbones are not known and some declared implant failures might be related to unfavorable stress values (123). The diameter, length, number, and positioning of implants influence force transfer and stress distribution around implants. The increase in the number length and diameter of implants improves the biomechanical behavior of implants, particularly when subjected to bending forces (159,160,161). Duyck et al. (2000) assessed the dispersion and immensity of occlusal forces on implants carrying fixed prostheses. Higher forces were detected with a decreasing number of implants (162).

Kumar et al. (2016) researched the consequences of implant-supported removable prostheses in completely edentulous patients with reconstructed fibula free flaps. They indicate that in spite of clinically applying two implants being as successful as four implants, the amount of bone resorption around the implants in patients with two implants was considerably greater (163). In the present study, as the number of implants increased, not only the stress on the implant-bone surface but also the stress on the mandible-fibula junction decreased. When looked at from the point of Total deformation, the result was again in a decreasing direction. Although there are many studies defending this idea, there are studies that do not support this idea.

Şimşek, B et al. (2006) 4.1 mm diameter and 10 mm length implants were used and implants were placed in 0,5 cm, 1 cm, and 2 cm intervals. 70N vertical 30N oblique force applied. The model was separately analyzed for vertical and oblique load sets. As a result, they recommended 1.0 cm as the optimum inter-implant distance after evaluation of stress distribution in the cortical and trabecular bone around the posterior mandibular implants (164). Latifi F et al. (2022) In his study, he created 2 models with fibula reconstructed mandibula, in the 1st model, they placed 3 implants with 11 mm intervals, in the 2nd model, 4 implants were placed 7.8 mm apart and applied 300N vertical and 50N oblique force. The model with four implants causes more stress on titanium units and surrounding bone (165). Thiyaneswaren N et al. (2014) observed and compared stress around implants in various normal and fibula reconstructed mandible models using FEA. Under 200N vertical force, they obtain higher stress values at a larger area of reconstruction models. Stress is higher around distal implants in long areas of reconstruction. They mentioned that increasing the number of implants with an increased anteroposterior spread may decrease the stress around the implants (139).

The result of the study did not support this view, different results were found in our study, as the distance decreased, the stress decreased. There are implications for the fibula being more cortical, there is better stress distribution, and we found fewer stress values in the closer placement of implants in our study. When look at the Von Misses stress values in the models that consider as monocortical and bicortical, where 3 implants are placed in the central position in the fibula with 3-7-10 mm intervals, it was observed that the least stress was in the bicortical model, in which the implants were placed 3 mm apart. In the light of these data, the thought that it could be this way the 3mm spacing and bicortical placement are ideal as variations in which the distance between the implants and the stress will be optimal and reduce the stress.

Kyung-Hoi Heo et al. (2018) researched the stresses of implants in the reconstructed mandible with a fibula flap. 3.3 mm in diameter in the canine region and 4.0 mm in diameter in the premolar and molar region, a total of 3 implants were inserted. 300N oblique force was applied to both implants on the reconstructed fibula and natural teeth on the mandible. All implants were determined to be 15 mm in length and an FEA study was performed on the model. Natural teeth showed fewer stress distributions than implants. Stress was condensed at the neck of the implant fixtures with a higher degree of stress around the distal implant. In addition to, the posterior region of the fibula showed stress concentration. Also, the splinted implant prosthesis showed more favorable stress and less displacement than separated models in the reconstructed mandible (98). In the present study, stress concentrations were seen in distal implants. Therefore, according to results of the study an increase in the number of implants and placement of distal implants will reduce and distribute the stress in large-defect reconstructions. Cheng et al. (2019) used finite element analysis to evaluate stress distribution and displacement of the reconstructed mandible with the fibula flap in different vertical positions. The fibular graft was placed at the superior position, intermediate position, and inferior position between two residual mandibular segments. A 70N-190N vertical force was applied. The maximum stress and strain are found at both the posterior border of the graft and the contralateral condyle area. Total Deformation occurs near the interface of the fibular graft and the anterior segment of the mandible (97). Ying T et al. (2006) investigate the biomechanics of the mandible following reconstruction with autogenous bone grafts by FEA. 120N, 150N and 200N vertical force applied. They reported that the maximum Von Misses stress occurred at the graft-bone binding interface near the molar region at 69,354 MPa. Furthermore, as the defect size increases, the stress increases, and more stress occurs in the reconstructions involving the coronoid process. The unreconstructed side condyle and mandibular angle mainly carry the stress. They also reviewed the 3D biomechanics of the reconstructed mandibula with the iliac and fibula autogenous bones by FEA in four different models. They mentioned that Von Misses stress dispersion was greater at different regions repair, a huge amount of stress concentration in the border of graft at posterior boundary and anterior edge (166). In the present study, also saw these results throughout our model in which we placed 1 implant at a distance of 3-7-10 mm from the step. However, as the number of implants increased, the force on the condyle decreased.

Peng Li et al. (2013) investigate the Von Mises and Total Deformation values in the mandible reconstructed by using a custom-made plate with the FEA method, and evaluated the stress distributions in the model by applying 300N vertical direction. The Von Misses stress in all parts of the model max 50,9 Mpa to min 0,1 Mpa. The index of total deformation was from 0,018 to 0 mm with the maximum point at the front part of the plate (140). El-Anwar M et al. (2016) researched the stress values induced by masticatory forces (100N applied vertically) on removable prosthesis supported and retained by bar splinted implants placed in the reconstructed mandible with vascularized free fibula flap. 3 implants were placed, the anterior and middle implants were 5 mm in diameter and 11 mm in length while the posterior implant was 3.5 mm in diameter and 11 mm in length. The implants acted in typical behavior with higher stress at the neck region and Total Deformation values found high at the anterior part of the overdenture (167). According to the before-mentioned studies, more stresses occur on the grafted bones rather than the residual mandibular segments. As the size of the defect increases, the Von Mises stress and Total Deformation values increases (74,97). In the mandible which reconstructed with fibula flap 150N vertical force applied, 30 mm defect showed more stress values than 10 mm defect, and this stress was observed in the posterio-superior portion on fibula at the posterior junction with the mandible (168). When Von Misses stress data was evaluated throughout the model in our study, stress concentrations were observed in similar regions with the studies. We obtained similar results with the studies. When the data were evaluated, as the number of implants increased, Total Deformation and Von Misses stress values decreased.

Hidalgo et al. (1989) informed that the border between transplanted fibular graft and the mandible was stable. However, limited study has researched the benefits of implants inserted at border between host bone and bone grafts (9). Ken, Y et al (2015) in the study, they created the fibular model (FM) in which worked in the fibula, and the transplantation models (TM) in which worked at the junction of the mandible and fibula. 100N vertical force applied and implant positioned centeraly. An implant 4.0 mm diameter, 10 mm length placed monocortically , then 4.0 mm diameter 15 mm length bicortically to the junction of the fibula and mandible model, and then fibula model. Results were evaluated with FEA. They report that Von Misses stress values are lower in bicortical placement than monocortical in fibula bone. However there were no important distinction between fibula model and transplantation model (133).

The present study, observed more stress in implants placed close to the graft-bone junction or even at the junction, especially in models with bicortical placement, stress was observed more than monocortical placement. When the advantages of the previously mentioned bicortical location compared to the monocortical location and the positive aspects in stress distribution are considered, the opposite result was observed at the graft-mandible junction. As a result, stress increases in bicortical localization compared to monocortical. Stress intensifies in this area and the apex of the implant, especially in implants that coincide with the junction surface. This creates the question of whether it is right to place an implant in this area.

There is no study examining the proximity of the implants to the edge of the fibula, so the data were evaluated internally. As a result of implant placement at a distance of 0.5 mm-1 mm-2 mm to the edge with 10 mm intervals: There was no significant difference in Total Deformation. Total deformation mostly depends on the number of implants and the distance between them. When we look at the Von Misses values, the maximum stress was seen in the neck of the distal implant, located 1 mm close to the edge of the fibula. Stress values were less in bicortical location compared to monocortical location. While the stress was 31.59 MPa at 1 mm distance, the value decreased to 17.93 MPa at 2 mm distance. Values at 0.5 mm close were meaningless, we think it might be because of perforation. The present study show that, there is a risk of perforation with a thickness of 0.5 mm to fibula edge. The least stress was observed at 2 mm closeness and bicortical location.

The results of the Von Missess and Total Deformation data obtained from the bicortical and monocortical placements of the implants that we placed in different lengths and positions in the mandible reconstructed with a free fibula flap, in 4 main models and a total of 19 models.

- As the number of implants increases, the stress at the junction with the mandible decreases. Also, Total Deformation decreases, Von Misses stress around implant-bone surface decreases.
- Monocortical or bicortical insertion; does not affect the Total Deformation. Placement of implants with 3 mm spacing causes less Total Deformation values than 10 mm spacing.
- There is no significant difference between monocortical and bicortical implant placements with 10 mm apart insertion. The stress on the bone is less than 7 mm and 10 mm when placed with a 3mm spacing.
- The least stress is observed in the bicortically localized implants with 3mm apart alignment.
- Bicortical implant placement causes 50% increase in stress in locations close to the step. Stresses appear at the junction of the mandible and fibula.
- High stress values were observed in the implants placed monocortical with a distance of 1mm to the edge. There is a risk of perforation and dehiscence when placed 0.5 mm close to the edge. Optimum stresses were observed in the bicortical location at a distance of 2 mm from the edges.
- With this study, the success of fibula grafts and the long-term and effective preservation of tissue integrity of implants applied in fibula grafts are the uniqueness of our study. We think that studies about this issue will have positive effects on the patient's comfort and the active use of restoration and will reduce the complications that may occur after surgery.

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7. APPENDICES

7.1. Ethical Approval

T.C. YEDİTEPE ÜNİVERSİTESİ

Sayı : 37068608-6100-15- 1724 **11/07/2019**
Konu: Klinik Araştırmalar
Etik kurul Başvurusu hk.

İlgili Makama (Yahya Tanoğlu)

Yeditepe Üniversitesi Ağız Diş ve Çene Cerrahisi Ana Bilim Dalı Dr. Öğr. Üyesi. Fatih Cabbar 'ın sorumlu araştırmacı olduğu **"Serbest Fibula Grefti İle Rekonstürükte Edilen Çenelerde Dental İmplantların Oluşturduğu Stresin Sonlu Element Analizi İle Değerlendirilmesi''** isimli araştırma projesine ait Klinik Araştırmalar Etik Kurulu (KAEK) Başvuru Dosyası **(1682)** kayıt Numaralı KAEK Başvuru Dosyası), Yeditepe Üniversitesi Klinik Araştırmalar Etik Kurulu tarafından **10.07.2019** tarihli toplantıda incelenmiştir.

Kurul tarafından yapılan inceleme sonucu, yukarıdaki isimi belirtilen çalışmanın yapılmasının etik ve bilimsel açıdan uygun olduğuna karar verilmiştir (**KAEK Karar No: 1072**).

Prof. Dr. Turgay ÇELİK
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8. CURRICULUM VITAE

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Educational Status

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