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Sloped marginal configuration design of implants as an alternative innovation to the grafting operations: a three-dimensional finite element analysis

Mehmet Emin Toprak

Department of Oral and Maxillofacial Surgery, Gazi University, Faculty of Dentistry, Ankara, Türkiye

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ABSTRACT

Aim: Dental implant operations often require bone grafting due to bone resorption in the buccal area, which make the treatment more complicated, increase the risk of complications, and results in extra costs and prolongation of treatment. This study aimed to evaluate the biomechanical behavior of the implants with a sloped marginal configuration design in the alveolar ridge with a level difference between the buccal and lingual bone levels using three-dimensional finite element analysis (FEA) method.

Material and Method: Two implant models with different marginal configuration designs were used in this study. Implants were placed in the posterior edentulous mandible models in which the buccal region had a 2 mm more resorption according to lingual region which were created by imitating natural bone resorption with FEA. Bone grafting was performed on the exposed buccal surface in the conventional flat marginal configuration implant model (Model 1). In contrast, the sloped marginal configuration implants were compatible with the difference in bone level and placed directly without any additional surgical procedures (Model 2). Than three unit fixed partial dentures were designed. The design of cortical and cancellous bones, prosthetic components, implants, abutment screws and abutments covering those in the edentulous mandible models were transferred to digital three-dimensional models that were created to mimicking the real structures. The models were fixed below and behind of the mandible with zero movement. Load transfer characteristics of both models under these essential limitations were evaluated under 200N foodstuff force.

Results: The highest von Mises stress value was observed as 69.300 MPa in Model 1 and 126.870 MPa in Model 2. The maximum principal stress values were 28.236 N/mm² and 63.449 N/mm²; the minimum principal stress values were 38.346 N/mm² and 43.643 N/mm² in Model 1 and Model 2, respectively. The highest von Mises stress value, maximum principal stress and minimum principal stress values were found higher in Model 2 which was created with sloped marginal configuration design of implants but all values were observed within acceptable physiological limits.

Conclusion: The sloped marginal configuration design of implants can be a non-invasive and more economical treatment alternative modality compared to conventional flat marginal configuration implants with advanced surgeries during implant placement.

Keywords: Dental implant design, grafting, sloped marginal configuration, innovation, biomechanics

INTRODUCTION

Dental implants have become widely used in the oral rehabilitation of complete or partial edentulous patients in recent years. Numerous studies conducted over the years have demonstrated the success of using implants in the dental treatments (1). A successful dental implant treatment requires osseointegration of the implant surface with the surrounding bone. In addition, dental implants should be placed in ideal position, and have hard tissue components and adequate soft tissue contact. Compatibility between the bone and the soft tissues is crucial for the successful, comfortable and cosmetic outcomes of the implant treatments (2). Selection of the dental implant type may be affected from alveolar crest anatomy of the placement site. Bony defects and insufficient bone dimensions can be compelled to apply various surgical procedures, such as resection or bone augmentation, in the surgical site due to prepare the bone morphology before placing the implant (3,4).

Different reasons cause to bony defects with variety of sizes, and it has been documented because of alveolar crest remodeling after tooth extraction. Clinical studies have shown that the horizontal dimensions of the alveolar

Corresponding Author: Mehmet Emin Toprak, dt.mehmetemintoprak@gmail.com
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crest generally decrease, and the width of the alveolar bone significantly decreases, especially in the first three months following the tooth extraction. Resorption of the buccal side of the alveolar crest has been demonstrated to be substantially significant than that of the lingual side (4-6).

The level differences between the buccal and lingual crests have been reported to provoke certain difficulties during implant surgeries. When the implant is placed by taking into consideration the lingual bone height as a reference, the buccal part of the implant is not completely submerged into the bone, so that this condition requires bone grafting subsequently. On the other hand, when the buccal bone level is taken as a reference, the implant is embedded into the bone at the lingual area and a resection osteotomy is needed to equalize the planes (7,8).

Advance surgery techniques including bone grafting in the implant marginal configuration areas may be necessary for immediate or delayed implant placements in order to eliminate the level differences. With the developing implant technology, implants with different marginal configuration designs mimicking the natural contour of the alveolar crest have been introduced into the market. A lot of studies reported high survival rates and stable soft tissues around the implant for this sloped configuration (7,9,10).

Dental implant performance and the distribution of forces in the implant and the surrounding bone has been investigated using finite element analysis (FEA) to predict potential failures. FEA has several advantages, such as reliable stress and strain distribution, simple model modification, and accurate representation of complex geometries. FEA can be used efficiently in dentistry to assess the biomechanical responses of dental implants, prostheses, and bone structures simulating chewing forces, and serve as a guide for clinical applications (11-13).

Biomechanical behavior can completely alter whilst changing the design of implant. Therefore, it is important to examine different and complex designs of implants and the surrounding bone using FEA. Different marginal configuration designs of the implant illustrated similar biomechanical behavior with conventional flat marginal configuration dental implant while presence of different buccal and lingual bone levels (14).

The purpose of this study is to evaluate the biomechanical behavior of implants, prosthetic structures and the adjacent bone by using grafted conventional flat neck implants and sloped implants with a design to tolerate the buccal bone resorption in posterior edentulous mandible models using three dimensional FEA.

MATERIAL AND METHOD

Materials and methods used in the study don't require ethical committee approval and/or legal specific permission because of the study design. All procedures were carried out in accordance with the ethical rules and the principles.

Model Design

The 3D geometry data of the edentulous mandibular model with a 2 mm cortical bone layer surrounding the cancellous bone and 2 mm mucosa covering this structure, was obtained from the Visible Human Project (US National Library of Medicine) using VRMesh Studio (VirtualGrid Inc, Bellevue City, WA, USA) software and Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103 USA) software programs.

A computer with Intel Xeon ® R CPU 3.30 GHz processor, 500gb Hard disk, 14 GB RAM and Windows7 UltimateVersion Service Pack1 operating system was used to arrange and homogenize the three-dimensional mesh structure. The components of implant and prosthesis were scanned three dimensionally using an optic scanner (Activity 880, SmartOptics Sensor Technick GmbH, Sinterstrasse 8, D-44795 Bochum, Germany). VRMesh Studio was used to constitute three dimensional images that were developed from the obtained images. The models created in the standard triangle language (.stl) format were imported into Rhinoceros 4.0 software. Compatibility between prosthetic components, implants, abutments and bone structures was achieved and load was applied using the Boolean method with Rhinoceros.

A mandibular model with a buccal bone level that is 2 mm lower than the lingual bone was created in the posterior region, starting from the first premolar #44, and including the first molar #46. Following the decomposition process, three-dimensional models were created using the 3D Complex Render method, resulting in the modeling of bone tissue. Cancellous bone was obtained from the bone tissue with the offset method.

The design of cortical and cancellous bones, prosthetic components, implants, abutment screws and multiunit abutments covering those in the edentulous mandible model were transferred to digital three-dimensional models that were created to mimicking their real structures. The process of modelling was completed upon the placement of the models produced in three dimensions with Rhioceros software in alignment with the correct coordinates. The meshed models in Rhinoceros were transferred to the FEA program (ALGOR.FEMPRO, .Algor, Beta Drive Pittsburg, PA, USA) for solid modeling while maintaining the three-dimensional coordinates. Occlusal load was applied as foodstuff design to create a more realistic simulation of the mastication.

In this study, two implant models with different marginal configuration designs were used, that are the Quattrocone implant made of Grade IV titanium with a standard conventional flat marginal configuration design (Medentika Straumann Group, Calw, Germany) and the Quattrocone30° implant made of Grade IV titanium with a sloped marginal configuration design (Medentika Straumann Group, Calw, Germany) (**Figure 1**).

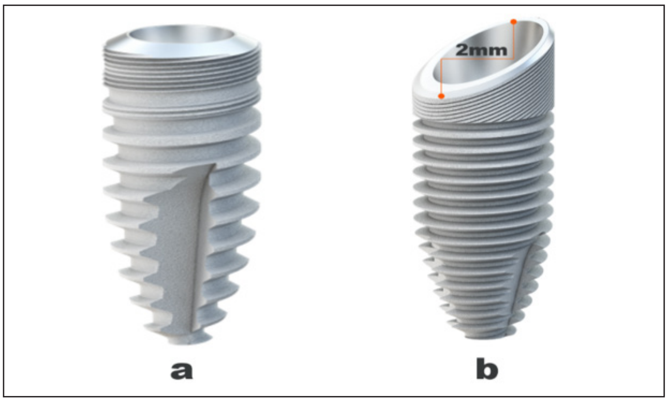

Figure 1. a) Conventional flat neck implant b) Implant with sloped marginal configuration

Model 1: Two standard conventional Grade IV titanium implants (4.3 mm in diameter – 11 mm in length, Quattrocone, Medentika Straumann Group, Calw, Germany) were placed axially in tooth areas #44 and #46 of the edentulous mandible. A bone design was created that fully encloses the implant on the lingual, mesial, and distal. Bone grafting was done to the exposed buccal implant surface due to the difference in buccal bone level. 5-mm titanium abutments and internal screws connecting the abutment to the implant were designed on these implants. Three dimensional finite element models of the implants, abutments, adjacent cortical and cancellous bone, and prosthetic structures were modelled and a screw-retained porcelain fused to cobalt-chromium metal fixed partial denture was designed in both models (**Figure 2**).

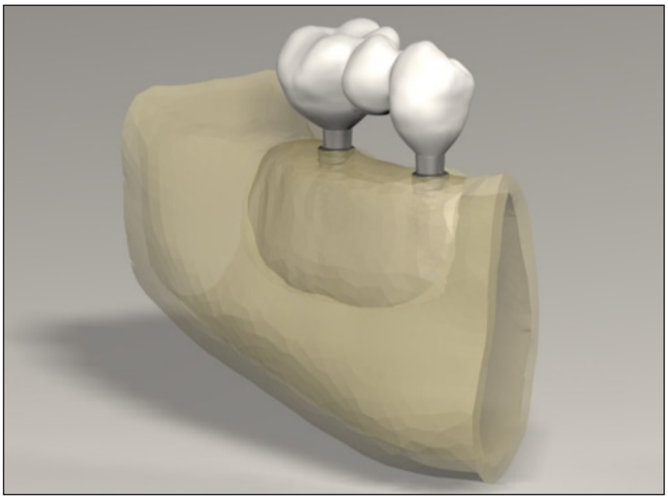

Figure 2. Model 1: Grafted buccal bone wall for implants with conventional marginal configuration design and the prosthetic components

Model 2: Two implants with a sloped marginal configuration (4.3 mm in diameter - 11mm in length on the lingual; 9 mm in length on the buccal, Quattrocone30°, Medentika Straumann Group, Calw, Germany) were placed axially on the areas of #44 and #46 in the edentulous mandible to be compatible with the difference in bone level. Bone design was created that fully encompasses the implant from the lingual, mesial, distal, and buccal sides. 5-mm titanium abutments and internal screws connecting the abutment to the implant were designed on these implants. Three dimensional finite element models of the implants, abutments, surrounding cortical and cancellous bone and prosthetic structures were modelled and a screw-retained porcelain fused to cobalt-chromium metal fixed partial denture was designed in both models (**Figure 3**).

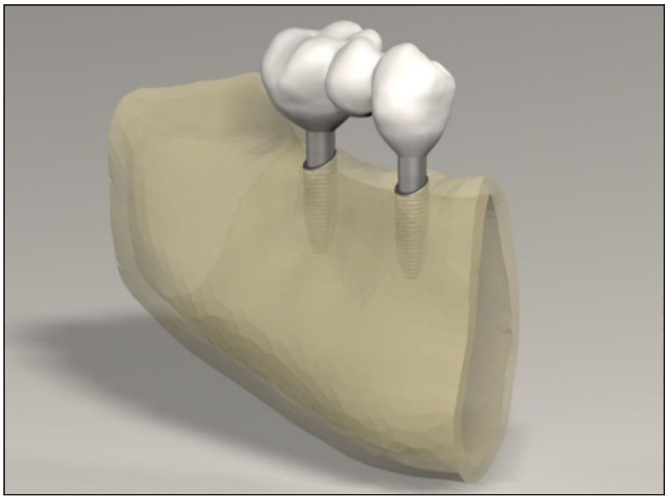

Figure 3. Model 2: Implants with sloped marginal configuration designed for bone resorption in the buccal side and prosthetic components

The number of nodes and elements used in mathematical models including scenarios were determined as 293358 nodes and 1510122 elements for Model 1, and 340720 nodes and 1843448 elements for Model 2.

Meshing Procedure

The models were created geometrically with the VRMesh software and then transferred in .stl format to the ALGORFEMPRO software for analysis and assessment. The structures were constructed and assigned material values in the models (the Poisson's ratio and the modulus of elasticity), which are used to define their physical qualities. The solid body characteristics were accepted as elastic, linear, isotropic, and homogenous by the program. The characteristics of the materials were developed by using the characteristics in the literature as an example (13-19) (**Table 1**).

Table 1. Mechanical characteristics of the materials used for the FEA

	Modulus of Elasticity (GPa)	The Poisson's Ratio
Cortical bone	14	0.30
Cancellous bone	1.4	0.30
Titanium (Grade IV implants and abutments)	110	0.35
Porcelain	96	0.29
Cobalt-chromium metal framework	218	0.33
Graft (medium stiff)	2	0.30
Food stuff	200	0.29

GPa: GigaPascal

Essential Limitations

The models were fixed below and behind the mandible with zero movement at each degree of freedom (DOF). A total of 200 N load was applied with foodstuff from mesial to distal of denture that was distributed with 50 N to the first premolar area, 50 N to the second premolar area, and 100 N to the first molar area, and then analyses were performed for each model (**Figure 4**).

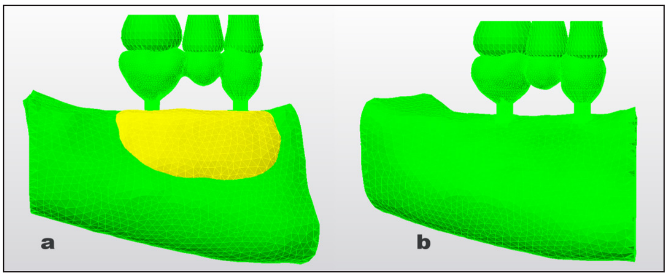

Figure 4. a) Foodstuff loading for Model 1 b) Foodstuff loading for Model 2

Von Mises analyses evaluate fragile materials such as implants, abutments, abutment screws, and prosthetic components. The maximum principal stress (Pmax) refers to the tensile stress, and the minimum principal stress (Pmin) states to the compression stress for flexural materials like cortical and cancellous bone (3,20). In this study, von Mises analyses were performed for implants, abutments, metal framework and prosthetic components while Pmax and Pmin were evaluated for cortical and cancellous bones. Then, a comparative analysis was performed between the models. The maximum equivalent von Mises value is observed on the image for each model. The results of the analyses were quantified and converted into color-coded visual materials. Red color is indicated the Pmax, and blue color is referred to the Pmin.

RESULTS

Both models had a similar stress distribution on the fixed partial dentures. The molar area showed that higher stresses rather than the premolars. A similar stress distribution was observed in the both groups and metal frameworks. The stresses were typically observed high around the implant-abutment connection site, and this trend continued thorough the abutments and surrounding crestal bone.

The highest stresses were observed in the molar implants for both groups. The von Mises values were observed high in the marginal configuration of the posterior implants. Stress values were similar for abutments in each model as well as the abutments showed more equitable stress distribution in Model 2. The implant marginal configuration in the first molar area showed the highest von Mises stress value with 126.869826 MPa during the total loading of the three-unit fixed partial denture in the same model (**Figures 5, 6**).

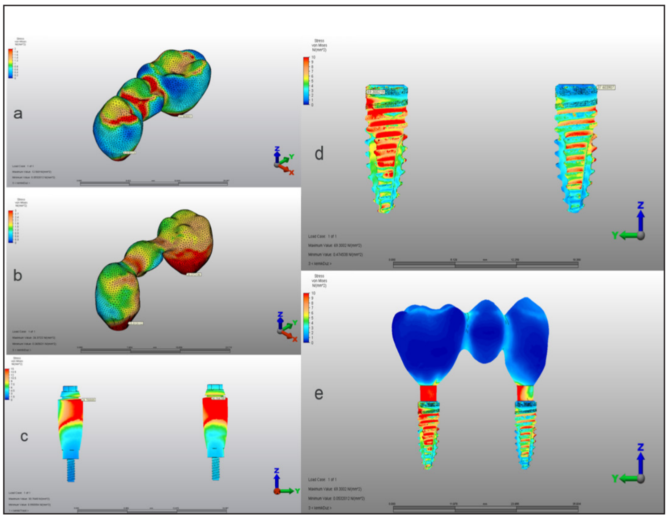

Figure 5. The von Mises stress values in Model 1 a) fixed partial denture b) metal framework c) abutments d) implants e) all components

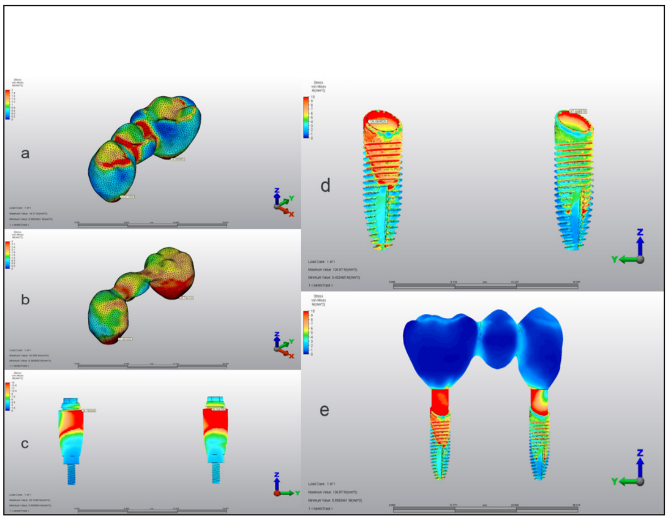

Figure 6. The von Mises MPa stress values in Model 2 a) fixed partial denture b) metal framework c) abutments d) implants e) all components

The von Mises stress values are presented for the implants, abutments, cobalt-chromium framework, and fixed partial denture components (**Table 2**).

Table 2. The von Mises stress values (MPa) in each implant area

	Model 1		Model 2	
	#44	#46	#44	#46
Porcelain fixed partial denture	9.970978213	12.569001	13.071959	14.309950
Cobalt-chromium framework	23.013112	25.551378	21.941692	24.134729
Abutment	21.910128	30.471224	26.750005	30.764798
Implant	37.603907	69.300219	47.448879	126.869826

MPa: MegaPascal

Pmax values were intensified around the lingual areas, and that was increased through the posterior regions in the both models. Connection area between the posterior implant marginal configuration and the lingual cortical bone has the greatest Pmax in Model 2 (63.4487 N/mm²).

Pmin values were intensified around the buccal areas. The grafted marginal configuration surface showed substantially less compressive stress in Model 1. Therefore, it was concluded that the Pmin values were higher in the cortical bone around the posterior implants' marginal configuration in the both models. Connection area between the posterior implant marginal configuration and the buccal cortical bone has the greatest Pmin in Model 2 (43.6434 N/mm²) (**Figures 7,8**).

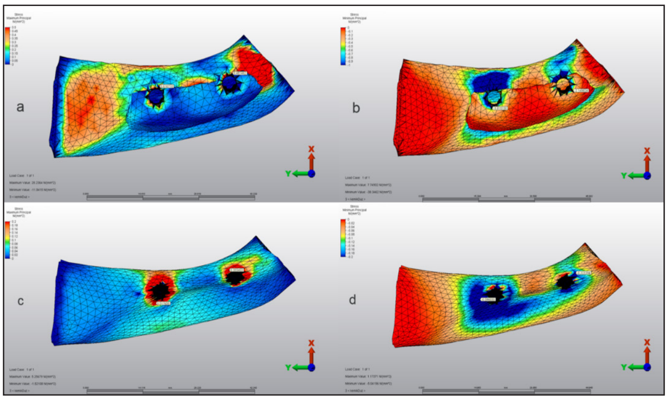

Figure 7. Model 1 a) cortical bone Pmax b) cortical bone Pmin c) cancellous bone Pmax d) cancellous bone Pmin

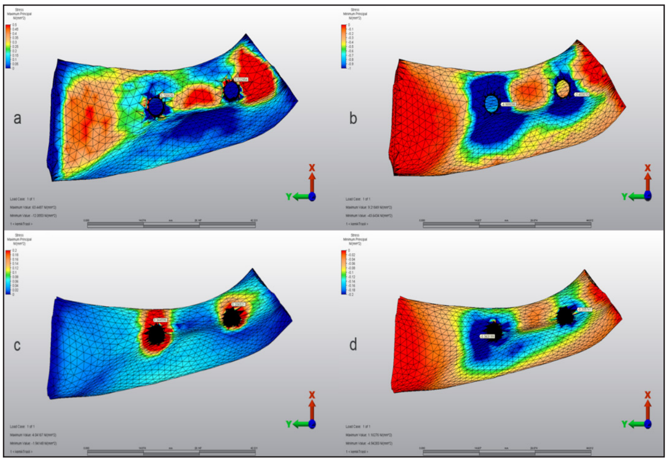

Figure 8. Model 2 a) cortical bone Pmax b) cortical bone Pmin c) cancellous bone Pmax d) cancellous bone Pmin

The Pmax and Pmin values of cortical and cancellous bones were presented for tested models (**Table 3**).

Table 3. The stress values created by the load on tested models (N/mm²)

		Pmax	Pmin
Model 1	Cortical bone	28.2364	38.3462
	Cancellous bone	5.25679	5.04196
Model 2	Cortical bone	63.4487	43.6434
	Cancellous bone	4.04167	4.94283

DISCUSSION

In this study, three dimensional FEA was used to investigate stress distribution characteristics of two different implant designs, that were conventional flat marginal configuration implants with bone grafting and sloped marginal configuration implants, in the light of literature which indicated that bone resorption patterns following tooth extraction (4,5,7,14,21).

Bone augmentation surgeries, including alveolar ridge split method, lateralization of the alveolar nerve, and maxillary sinus lift operations, can be performed in case of inadequate bone volumes, that would intercept appropriate placement of a conventional implant. However, such surgeries prolong the treatment time, increase the financial costs, and may also affect the general health status, especially in geriatric patients (13,19).

Irregularities in the alveolar bone can be encountered during the remodeling phase following tooth extraction. The buccal bone area is known to be resorbed more compared to the lingual. In dental implantology, the most of the stresses are stood out by cortical bone layer (22,23). The success in the implant marginal configuration area makes this data more important. The use of sloped marginal configuration implants is one potential treatment strategy to prevent bone resorption or grafting in the buccal area (22).

Numerous clinical studies have been carried out to evaluate the biomechanical aspects of dental implant design (1,10,14,21,22). The quality and strength of osseointegration, and the bone-implant connection are crucial to acquire the long-term success of implant treatment in edentulous jaws. However, there have not been defined for optimum implant design features to be considered as the best treatment outcome yet. Dental implant design can be improved to maximize strength, interface stability, and load transfer using appropriate materials, surface treatment, and groove shape (1,24).

The biomechanical characteristics of a dental implant, such as size, shape, geometry, and marginal configuration design, are significant for successful long-term outcomes.

Bone resorption in the marginal configuration of an implant is the most common manifestation of implant failure in the literature. Bone resorption may be induced by sex, surgical trauma, plaque accumulation, smoking, biological bone width, bone quality, implant design and biomechanical factors (11,13,25). Similar to other studies, it was determined that the stresses were mostly concentrated around the implants' marginal configuration and adjacent cortical bone to these regions in this study (8,10,11,13).

Abrahamsson et al. (9) conducted an experimental study on animals, and they placed different dental implant types into resorbed jaw with lower buccal bone height compared to the lingual bone level. The authors investigated bone loss characteristics of conventional implants and sloped marginal configuration implants that were fully compatible with the marginal bone area of implant marginal configuration after the osseointegration. The histological examination of the buccal bone defect showed that any marginal bone support was observed on the exposed surface of the implants with the conventional marginal configuration design, while the bone level was stable in the sloped implants. In the current study, the sloped marginal configuration implants exhibited acceptable biomechanical behaviors close to the conventional dental implants with bone grafting.

Moreover, two prospective, multicenter studies that evaluated applications and long-term results of sloped marginal configuration implants in humans. These studies showed that clinical results were promising, and these type of implants could be an alternative to conventional implants with complicated surgeries and additional treatment costs (7,21). Schiegnitz et al. (22) highlighted that the sloped marginal configuration implants might be challenging to maintain stable and resilient peri-implant keratinized mucosa compared to conventional implants.

The tensile strength threshold value is 680 MPa for dental implants which made from a grade IV cold-worked titanium (14,15). In the present study, the Von Mises stress values of grade IV titanium implants were found to be within acceptable limits under an occlusal load simulating a 200N mastication in tested groups. As the von Mises stress values are much lower than the maximum strength values (680-1110 MPa), that were obtained for dental implants made by the titanium alloys (14-16), in both models of this study. The risk of fracture in implants and abutments is almost non-existent.

The Pmax value has been reported to be around 100-121 MPa, and the Pmin value to be around 167-173 MPa to withstand without bone damage (16,26,27). Considering these values, the results of our study are well below the maximum acceptable values, and do not pose any problem for the bone. Thus, implants with a sloped marginal configuration can be used within the confidence limit instead of performing a complicated, costly, and advanced surgery such as bone grafting.

One of the limits of the study is that the osseointegration between the implant models used in the FEA and the bone was assumed as 100% bone-implant connection. It is known that this cannot be achieved in clinical conditions. In the literatures, maximum bone osseointegration was reported that between 75% and 90% histologically by researchers (15,17,28). Other limitations of the current study included that the equal consideration of the bone healing and transformation potential of the graft material. Moreover, bone resorption pattern presumed same level on the buccal area due to essential limitations. Based on the results of this FEA study, multicenter clinical studies should be conducted to evaluate positive findings about implant with sloped marginal configuration.

CONCLUSION

Grafting the marginal configuration areas of the conventional implants is an accurate approach in the posterior edentulous mandible with resorbed buccal area, but it is also possible to simplify the surgery, to reduce the clinical hours and the number of surgeries, and to avoid additional costs by using sloped marginal configuration implants. The.von Mises.stresses of.sloped marginal configuration implants were within the physiological limits, Pmax and Pmin values of the surrounding bone are acceptable. Sloped marginal configuration implants can be used as an innovative product that can facilitate the treatment process when a level difference exists in the bone. This specially designed implant can be a useful alternative treatment modality to conventional implants with advanced surgical operations.

ETHICAL DECLARATIONS

Ethics Committee Approval: The author of this article declare that the materials and methods used in the study don't require ethical committee approval and/or legal-specific permission because of the study design.

Informed Consent: Because of the study design, no written informed consent form was obtained from the patients.

Referee Evaluation Process: Externally peer-reviewed.

Conflict of Interest Statement: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that this study has received no financial support.

Author Contributions: All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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