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Does a sloped neck implant design facilitate for All-on-4 surgeries? A three-dimensional finite element analysis

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Abstract

Aim: In the treatment of edentulous resorbed mandibles using All-on-4 concept, the distal part of posteriorly tilted implants with a conventional flat neck design is usually embedded in the bone, which may lead to improper installation or positioning of angled multiunit abutments. Bone trimming from the distal area, where the implant neck is embedded in the bone, is typically necessary to avoid this complication. This study aimed to evaluate the biomechanical behavior of a sloped marginal neck configuration of implant posteriorly tilted at 30° in edentulous mandibles using a three-dimensional finite element analysis (FEA).
Methods: The sloped neck implants were posteriorly tilted at 30° without any further operation in the edentulous mandibular model designed using the FEA. The tilted conventional flat neck implants were placed at the same length, diameter, and angle, and 2x2 mm of bone was trimmed from the distal area. Similar multiunit abutments, two conventional flat neck implants axially placed on the anterior side, titanium frameworks, and acrylic resin prosthetic dentures were created for both models. The biomechanical behaviors of the models were evaluated by applying a foodstuff force of 50 N to the incisors, 100 N to the premolars, and 150 N to the molar cantilever.
Results: The von Mises stress value of the sloped neck implants (158.489 MPa) was lower than that of the conventional flat neck implants (177.208 MPa). Both the maximum and minimum principal stress values in the surrounding cortical and cancellous bones were within the acceptable physiological limits.
Conclusion: Sloped neck implants can be placed easily and are less invasive than conventional flat neck implants; thus, they can be a treatment alternative that can facilitate the All-on-4 concept.

Keywords: Dental implant, sloped neck design, bone resorption, biomechanics, finite element analysis, All-on-4

Introduction

In the rehabilitation of edentulous jaws, there are a number of treatment options depending on the severity of bone resorption, including a variety of implant surgeries. Implant-supported fixed prostheses are a safe and effective treatment option. Severe resorption of the alveolar bone and crucial anatomical structures may affect the number, length, and diameter of the implants used and the design of implant-supported prostheses [1, 2].

The All-on-4 treatment concept was created to prevent damage to the inferior alveolar nerve and the mental foramen in severely resorbed mandibles and the pneumatic sinuses in the maxillae and to minimize the negative bending forces caused by cantilever extensions of dental prostheses. This treatment concept shows proven survival and success rates and has been accepted by dentists [2–4].

In the All-on-4 concept, two straight implants are placed in the anterior area, and two distally tilted implants are placed in the posterior area in the interforaminal region. The tilting of implants provides many biomechanical advantages, such as longer implant usage, increased primary stability and cortical anchorage, wider distribution of implants in the dental arch, shortening of cantilevers, and less stress transmission to implants [2, 5, 6].

An elongated cantilever can cause mechanical overload of the prostheses and an uneven distribution of stresses on implants, abutments, and prostheses. This leads to reduced success and survival rates for the implants [2, 3, 6]. The All-on-4 treatment concept aims to achieve maximum utilization of the residual bone and early functioning of the implants. Complex surgical procedures—such as sinus lift, nerve lateralization, and lateral or vertical bone augmentation (and therefore increased treatment costs)—can be avoided when implants are tilted [7–11].

Tilted implants that are placed posteriorly have a high potential for complications. The angle between the implant platform and the alveolar crest may be the cause and may lead to deeper pocket formation in the peri-implant areas, causing marginal bone loss. Using abutments of different lengths and angles on tilted implants, internal screws are positioned in the occlusal region [12]. Microorganisms and their toxins can accumulate between implants and incompletely seated multiunit abutments, which increases the risk of peri-implantitis [13].

In the All-on-4 concept, when posteriorly tilted implants with a flat neck design are placed, a level difference occurs in the bone between the distal and mesial surfaces of the implant neck. This level difference causes improper positioning of multiunit abutments, and consequently, additional surgical procedures are needed to correct the bone level [14]. Biological complications and aesthetic problems caused by the bone level difference around the neck of tilted implants have been managed with sloped implants. However, most clinicians have insufficient information about implants with a sloped neck configuration [12, 15].

Finite element analysis (FEA) has been an effective method for studying the biomechanical problem of dental implant applications [16, 17]. FEA element analysis has many advantages in investigating the biomechanical behavior of implant-supported fixed prostheses and numerically simulates the behavior of various dental biomaterials, restorative techniques, and prosthetic designs in terms of displacement and stress distribution under varying loading situations [18, 19]. It allows to simulate complex structures with irregular geometries precisely by resizing various dimensions and shapes of elements and the assessment and quantification of the biomechanical response of dental materials, implants, prosthetic components and the supporting dental structures [20, 21].

The aim of this study is to evaluate the biomechanical effects of the loading forces on simulated All-on-4 models with posteriorly tilted conventional flat neck implants and sloped neck implants.

Materials and Methods

Model design

The 3D geometrical data of a mandibular model with a residual bone height of 16 mm and width of 9 mm, interforaminal region length of 46 mm, cortical bone thickness of 3 mm in all directions, and cancellous bone diameter of 10 mm were obtained from the Visible Human Project (US National Library of Medicine) using VRMesh Studio (VirtualGrid Inc., Bellevue City, WA, USA) and Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA, USA). A 14 mm distance was created between the anteriorly and posteriorly tilted implants. The length of the distal prosthetic cantilever was 10 mm. A resorbed edentulous mandibular model was developed; each region was covered with 3 mm of cortical bone. After the decomposition process, 3D models were produced using the 3D complex render method, which helped in bone modeling. The cancellous bone was obtained from cortical bone tissue via the offset method.

A computer with an Intel Xeon R CPU 3.30 GHz processor, a 500 GB hard disk, 14 GB RAM, and the Windows 7 Ultimate Version Service Pack 1 operating system was used for arranging and homogenizing the 3D mesh structure, obtaining a solid model in three dimensions, and performing stress analysis via the finite element method. Meanwhile, an optical scanner (Activity 880, SmartOptics Sensor Technick GmbH, Sinterstrasse 8, D-44795 Bochum, Germany) was used for 3D scanning of the supplied implants and prosthetic fragments. Thereafter, 3D images were developed from the obtained scans using VRMesh Studio. The models created in standard triangle language (.stl) format were imported into Rhinoceros 4.0. Compatibility was established between the prosthetic components, implants, abutments, and bone layers using the Boolean method via Rhinoceros 4.0, and loading was performed.

The edentulous mandibular model's cortical bone design, cancellous bone design, prosthetic superstructure components, implant screws, and multiunit abutments were transferred to digital 3D models created to correspond to their actual structures. Modeling was completed when the created models were correctly aligned in three dimensions using Rhinoceros 4.0. The meshed models in Rhinoceros 4.0 were then transferred to the FEA program (ALGOR FEMPRO, Algor, Beta Drive Pittsburg, Pennsylvania, USA) for solid modeling, while preserving the 3D coordinates. Loading was performed with foodstuff designed to create a more realistic chewing simulation.

Two implant models with different neck designs were used in this study: a Quattrocone 30° implant made of grade IV titanium (Medentika Straumann Group, Calw, Germany), with a 2-mm sloped neck design, and a Quattrocone implant made of grade IV titanium with a conventional flat neck design (Medentika Straumann Group; Figs. 1a and 1b).

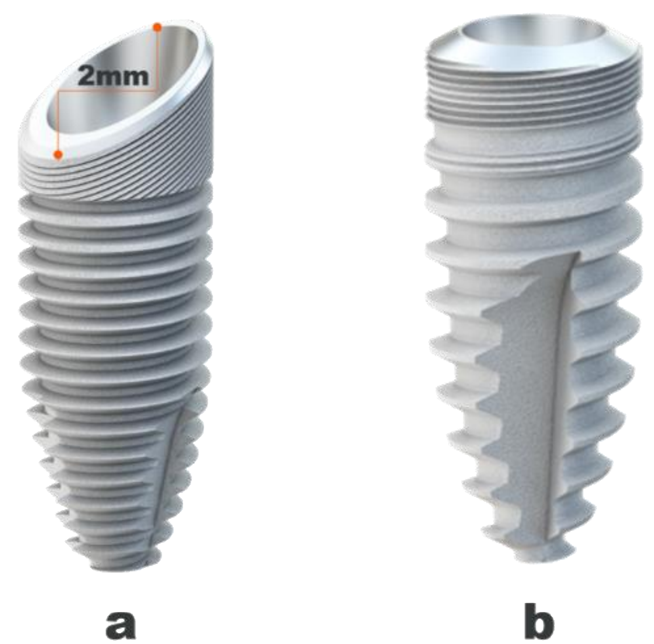

Figure 1. **(a)** Sloped neck implant, **(b)** Conventional flat neck implant.

Model 1: Two standard conventional implants (diameter 4.3 mm, length 13 mm; Quattrocone, Medentika Straumann Group) were placed axially into the interforaminal mandible's anterior region. Sloped neck implants (diameter 5.0 mm, length 13 mm; Quattrocone 30°, Medentika Straumann Group) were distally tilted at 30°, bordering the right and left mental foramens, without any further surgeries (Fig. 2). Thereafter, 5 mm straight titanium multiunit abutments were designed for the anterior implants. Angled multiunit abutments compatible with the tilted placement and sloped neck design to achieve 30° inclination to the occlusal plane, as well as internal screws connecting these abutments to the implants, were also designed. With a design similar to that of a 12-unit acrylic prosthesis consisting of a titanium framework in both models, 3D finite element models of implants, implant components, surrounding cortical and cancellous bones, and prosthetic dentures were simulated.

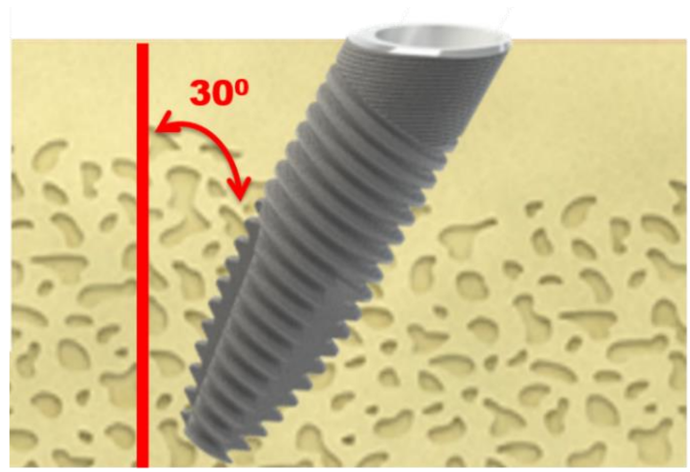

Figure 2. Sloped neck implant placement into the bone with distal tilting at 30°.

Model 2: Similar to the method in Model 1, two standard conventional implants (diameter 4.3 mm, length 13 mm; Quattrocone, Medentika Straumann Group) were placed axially into the interforaminal mandible's anterior region. Conventional flat neck implants (diameter 5.00 mm, length 13 mm; Quattrocone, Medentika Straumann Group) were distally tilted at 30°, bordering the right and left mental foramens (Fig. 3). Thereafter, 2 × 2 mm cortical bone was trimmed from the distal area where the conventional flat neck implant was embedded into the bone to properly place the angled multiunit abutment into the implant body. Five-millimeter straight titanium multiunit abutments were designed for the anterior implants. Angled multiunit abutments compatible with the tilted placement and sloped neck design to achieve 30° inclination to the occlusal plane, as well as internal screws connecting these abutments to the implants, were also created. With a design similar to that of a 12-unit acrylic prosthesis consisting of a titanium framework in both models, 3D finite element models of implants, implant components, surrounding cortical and cancellous bones, and prosthetic dentures were simulated.

The numbers of nodes and elements used in the simulated models (including scenarios) were 418141 and 1783454 for Model 1 and 352195 and 1479935 for Model 2, respectively.

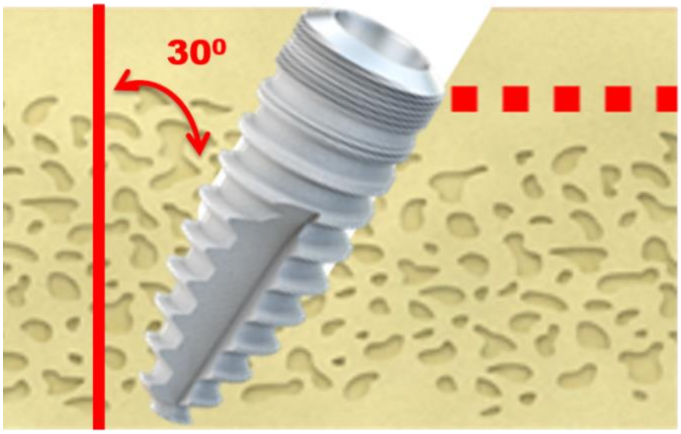

Figure 3. Conventional flat neck implant placement into the bone with distal tilting at 30°.

Meshing procedure

Following the models' geometrical production using VRMesh Studio, the models were transferred to ALGOR FEMPRO in .stl format to be prepared for analysis and evaluation. Material values (modulus of elasticity and Poisson's ratio) were assigned to the structures to describe their physical characteristics. The ALGOR FEMPRO program has accepted rigid body characteristics, such as elasticity, linearity, isotropy, and homogeneity. The attributes of the materials used in the model designs were based on the previously described characteristics (Table 1).

Table 1. Mechanical characteristics of the materials used for finite element analysis

	Young's Modulus (GPa)	Poisson Ratio
Cortical bone	14	0.30
Cancellous bone	1.4	0.30
Grade IV titanium (implants, abutments, screws, and frameworks)	110	0.35
Acrylic resin dental prosthesis	2.7	0.35

GPa: GigaPascal

Essential limitations

The models were fixed below and behind the mandible, with zero movement at each degree of freedom. The x symmetry was presented from the midpoint of the models. Loading was performed at 50 N in the incisors, 100 N in the premolars, and 150 N in the molar cantilever using foodstuff (Figure 4). These limiting conditions were the same in both models.

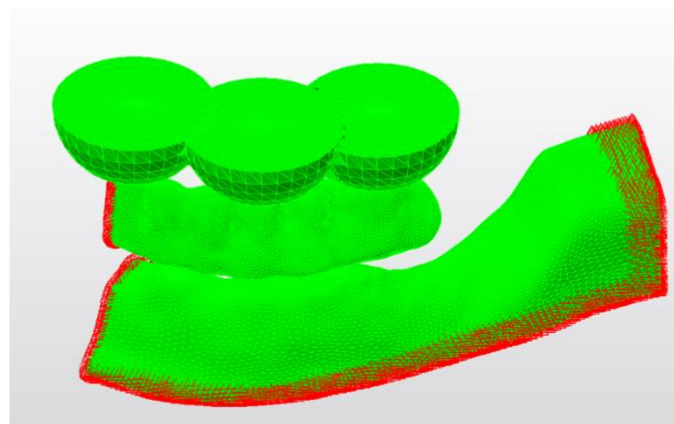

Figure 4. Foodstuff loading areas of prosthetic dentures.

Evaluation of the FEA results

The maximum principal stress (Pmax) and minimum principal stress (Pmin) on the cortical and cancellous bones were evaluated. Von Mises stress analysis was performed for the implants, abutments, metallic frameworks, and prosthetic components. The maximum equivalent von Mises value for each analysis is shown in Figures 5 and 6 for comparison. The analysis results were quantified and converted into color-coded visual materials. In Figures 5-7, the Pmax is indicated in red and the Pmin is indicated in blue. The software automatically calculates the values of the stress patterns at any location and reports them in megapascals.

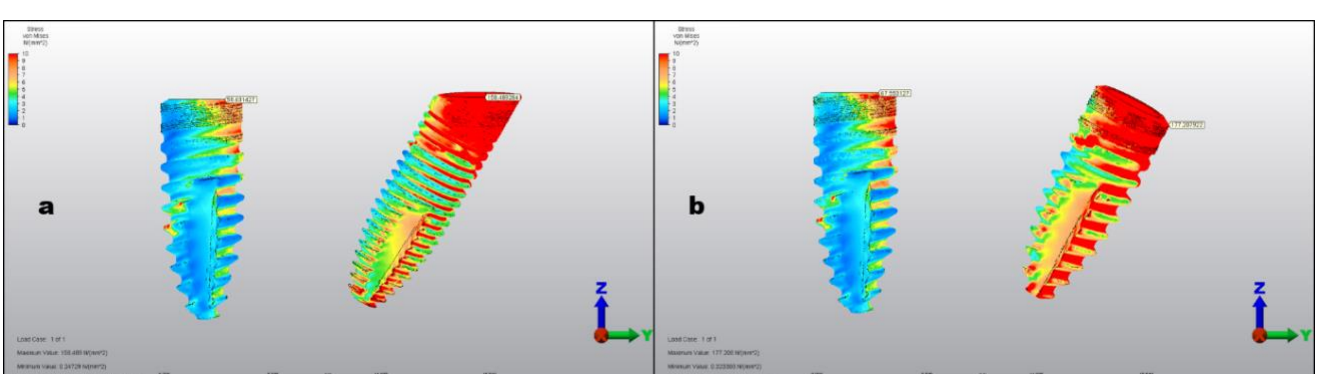

Figure 5. Von Mises stress values on the implants in Model 1 (a) and Model 2 (b).

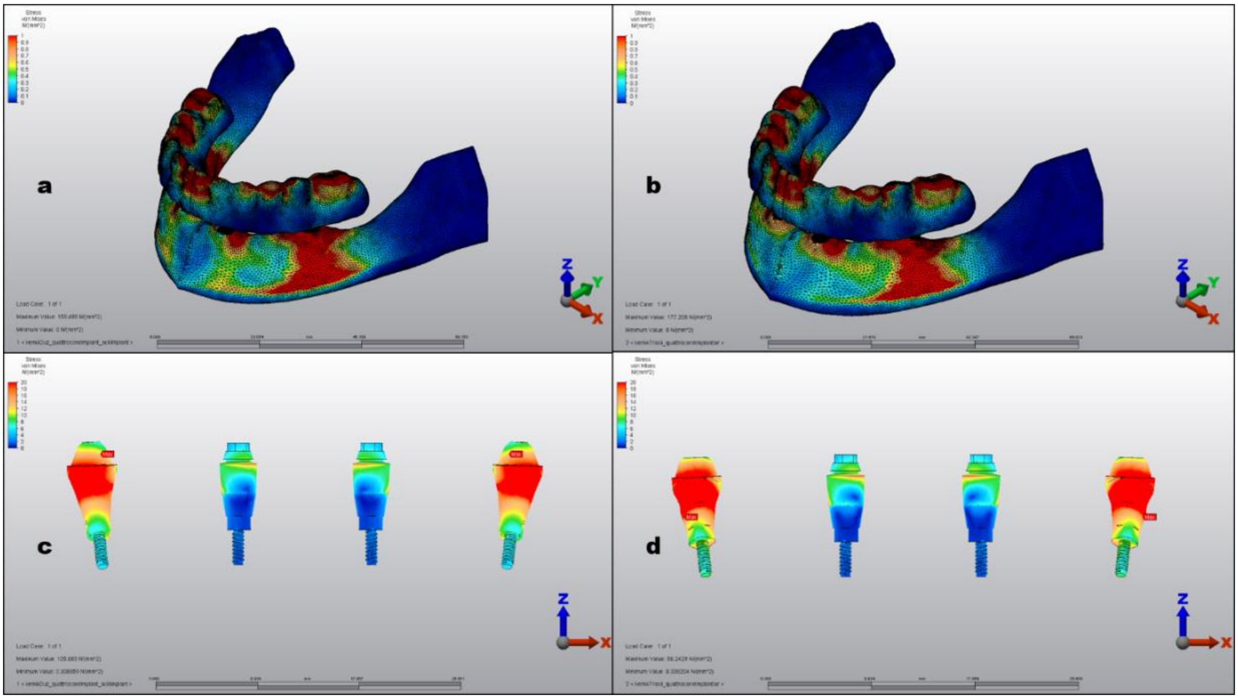

Figure 6. Areas where stress is concentrated in Model 1 **(a)** and Model 2 **(b)** and distribution of stress on multiunit abutments with sloped neck implants **(c)** and conventional flat neck implants **(d).**

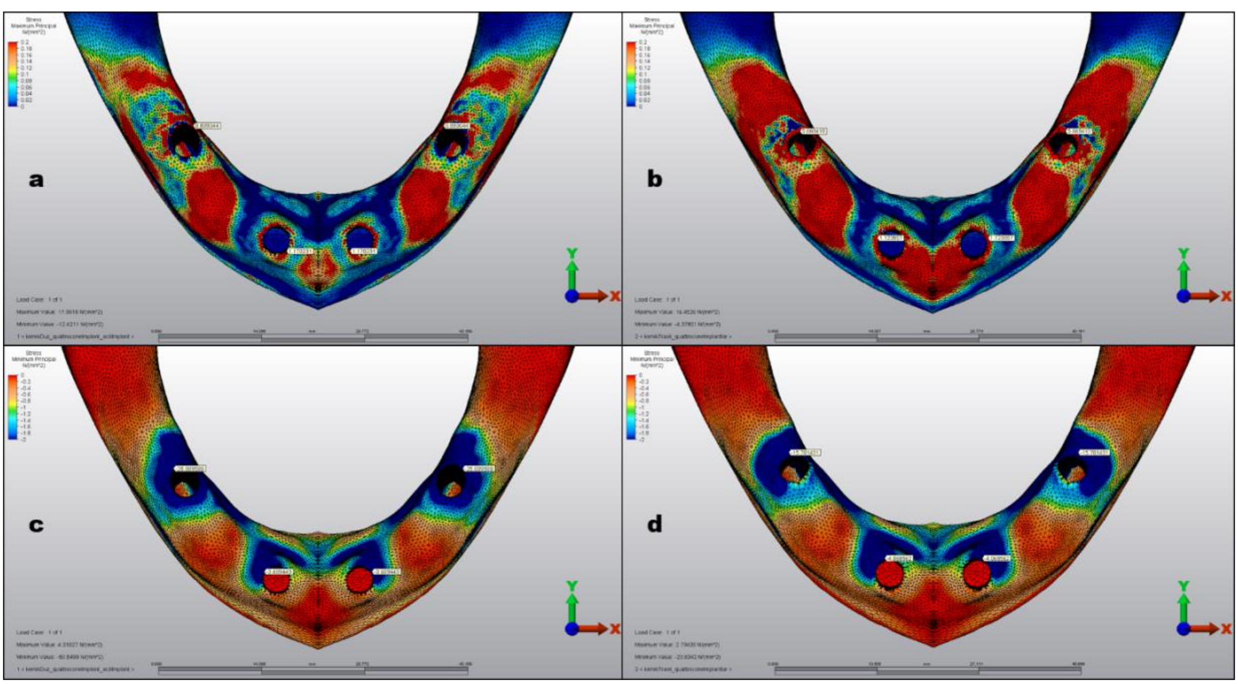

Figure 7. Pmax values in the cortical bone in Model 1 **(a)** and Model 2 **(b),** and Pmin values in Model 1 **(c)** and Model 2 **(d).**

Results

The highest von Mises stress value was measured on the distally tilted posterior conventional flat neck implants integrated into the cortical bone (177.208 MPa) in Model 2 (Fig. 5).

The biomechanical stress values were generally higher in Model 2 than in Model 1. The stress values were distributed more uniformly in Model 1 than in Model 2, and the stresses were concentrated in the neck areas, where the implants were connected with the abutments. Higher stress values were detected toward the distal cantilever region of the prosthetic components than toward other areas. Higher stress values were also noted in the angled multiunit abutment in Model 1. This difference might reflect better distribution of the loading forces on the sloped neck design, which might have distributed the loading forces more to the prosthetic components than to the surrounding bone

(Fig. 6). The von Mises stress values of the implants and prosthetic components are shown in Table 2.

Table 2. Von Mises stress values in Model 1 and Model 2.

	Model 1 (MPa)	Model 2 (MPa)
Anterior implant	58.631	67.553
Posterior implant	158.489	177.208
Anterior straight multiunit	32.960	41.719
Posterior angled multiunit	105.683	86.243
Metallic framework	54.1136	33.624
Acrylic dental prosthesis	11.872	12.8121
Total loading	158.489	177.208

MPa: MegaPascal

The Pmax in the cortical bone was equivalently distributed on the lingual and buccal sides, and the values were within tolerable limits for both models. The Pmax was more concentrated toward the posterior side in both models. While the Pmax showed a more proportional distribution in the cortical bone in both models, the Pmin was concentrated toward the lingual side of the cortical bone.

In Model 1, the highest Pmax value was noted in the areas close to the connection of the posterior implant neck with the cortical bone. The Pmax value in the cancellous bone was higher in Model 2 than in Model 1. The Pmin in the cortical bone was concentrated in the areas close to the lingual and distal sides, with the highest compression values observed in the cortical bone on the lingual side in Model 1 (Fig. 7).

The Pmax and Pmin values in the cortical and cancellous bones in the models are presented in Table 3.

Table 3. Pmax and Pmin values in the cortical and cancellous bones in the All-on-4 models with different implant neck designs (N/mm^2).

		Pmax	Pmin
Model 1	Cortical bone	17.9018	50.5498
	Cancellous bone	2.7544	3.96221
Model 2	Cortical bone	16.4526	23.8342
	Cancellous bone	6.32264	4.97476

Discussion

The biomechanical effects of the loading forces in the All-on-4 models of totally edentulous mandibles, which were designed with posteriorly tilted sloped neck design implants and conventional flat neck implants, were evaluated by FEA in this study. We found that tilted sloped neck implantation without any additional surgery could biomechanically counter the loads and facilitate the procedure for All-on-4 treatments. Therefore, this approach can be considered as an alternative to conventional implantation.

The remodeling process of the alveolar crest is initiated following tooth extraction. The horizontal dimensions of the alveolar crest generally decrease, especially in the first 3 months. The presence of defects or insufficient bone volume in the area where the implant treatment will be performed may require bone trimming or augmentation of the ridge with different graft materials to achieve adequate bone morphology for the implant operation [22, 23-25]. Implants with a specially designed neck area can be used in crests that have different bone levels, and they can show similar biomechanical behaviors to those of conventional flat neck implants [12, 15, 22, 25].

FEA allows the examination of complex structures with irregular anatomy under functional loads and the observation of biomechanical behaviors in dentistry [26]. However, the greatest disadvantage of the FEA method is that the essential limitations change the nature of the tissues during a stable simulation. Another disadvantage is that while the rate of osteointegration of implants is generally accepted as 100% in FEA studies, it can only reach as high as 75%-90% histologically [27-29]. The limiting conditions determined in models, including the direction and amount of applied forces, are other factors that limit FEA studies [24]. FEA studies have some limitations that difficulties in simulating biological dynamics, higher risk of human-based errors, and extensive advanced computation simulation time due to the complexity of numerical calculations, material properties, load values, and type of application.

The number of nodes and elements used in FEA studies is directly related to the sensitivity of those studies. In the present case, the number of nodes and elements was sufficient to maximize sensitivity, in agreement with previous studies [22, 24, 30, 31]. The functional and parafunctional loads produced by mastication are transferred to implants and surrounding tissues through the prosthetic components in implant-supported restorations. These loads cause deformation of the implants, prosthetic components, and surrounding bones, and implant survival and success are affected by these biomechanical factors [32]. In the All-on-4 concept, the posterior implants are tilted at different angles to assess the stress values. As tilting increases, the biomechanical stress also increases [24, 33]. However, a previous systematic review has reported that the implant angle in the All-on-4 concept does not affect bone resorption or implant success [34].

Tilted distal implants have a high potential for complications. This is caused by the angle between the implant platform and the crest, which can lead to deeper pocket formation or marginal bone loss in the peri-implant area. Supracrestal implant placement has been suggested to prevent this situation; however, a part of the implant neck will be exposed, as the surface of the implant will come in contact with the oral mucosa and, consequently, biological complications will develop [12].

The use of a sloped neck implant design facilitates surgeries by reducing the need for surgical procedures performed to equalize the bone level during implantation [14, 15, 25]. Implants with a sloped neck design, which were developed to tolerate the discrepancy between the buccal and palatal bone levels in immediate extraction sockets and to achieve aesthetic outcomes, have also begun to be used in the All-on-4 treatment concept [14]. However, limited studies have shown the biomechanical effects of the sloped design in this concept; our study is one of the pilot studies in this subject area.

Bone resorption in the crestal part of implants has been shown to be the main consequence of failure. Plaque accumulation and inappropriate loading conditions are also considered reasons. Kılıç et al. [35] and Bozkaya et al. [36] found that the cortical bone area sustains the most loading stresses, similar to our study.

Herein, the stresses were mostly intensified on the implant neck area. The maximum stresses have been shown to typically intensify on implant necks in previous FEA studies [37, 38]. The implant-abutment and abutment-prosthetic framework connections in distal implants are crucial for stress distribution in posteriorly tilted implants [38]. These connections aim to make the loading more vertical by using multiunit abutments on angled implants. Multiunit abutments do not cause excessive stress while tolerating implant tilting and allowing vertical loading [24].

Different implant designs have been produced for tilted implants using the All-on-4 concept. One-piece tilted implants with a standing multiunit abutment have been designed to prevent complications that may occur in the abutment-implant connection areas. Zincir and Parlar compared this implant design with the conventional two-part implant-abutment connection and reported that although the biomechanical stress values in single-piece implants are higher, one-piece tilted implants can be used within biomechanical limits [31].

The maximum loading resistance value of cold-worked grade IV titanium implants has been reported as 680 MPa [22, 27, 39]. Herein, the von Mises stress values of the grade IV titanium implants in both groups were within acceptable limits, with better results for the sloped implants than for the conventional implants.

The Pmax and Pmin values that the bone can tolerate without any damage are reported to be 100–121 MPa and 167–173 MPa, respectively [36, 39, 40]. The present results were within acceptable physiological limits. Considering biomechanical behaviors, a sloped marginal configuration of implants can be preferred in All-on-4 treatments, rather than the conventional flat neck design, to facilitate surgeries by eliminating bone trimming around the distal area of tilted implants.

In recent implantology, surgical guides are prepared using computer-aided software, and flapless surgeries are becoming more common over time. Not removing the mucoperiosteal flap ensures that tissue vascularization is not impaired, reduces surgical time, minimizes complications (e.g., pain, bleeding, and postoperative swelling), and increases patient comfort [14, 41, 42]. We believe that this strategy can also increase the comfort of physicians in flapless All-on-4 surgeries performed using a guide, since implants with a sloped neck design reduce the need for additional surgeries to the bone.

One of the limitations of this study is that the implants used in the FEA were evaluated as if there was 100% osteointegration to the bone. This result is not possible under clinical conditions, as different degrees of bone-implant surface connections occur on different surfaces of the same implant [27, 29]. Further, although the anatomy may vary even in the same individual, and the mandibles do not have a predictable resorption process at every point, the cortical and cancellous bones were modeled under equal conditions in each region, and the sloped implants were placed accordingly owing to the limiting conditions herein. Considering these unpredictable conditions at the surgical stage and the results of the FEA, the use of sloped neck implants in All-on-4 treatments should be supported by further data from clinical studies, and long-term follow-up should be performed.

Conclusion

In the All-on-4 treatment concept for resorbed fully edentulous mandibles, using implants designed with a sloped neck can facilitate required surgeries, reduce procedural time, increase patient comfort, and prevent additional costs, in contrast with performing an additional bone-shaving surgery to ensure the placement and positioning of multiunit abutments using standard neck implants when placing distally tilted posterior implants and removing the crestal bone. The von Mises stress values in the FEA with sloped neck implants and the Pmax and Pmin values in the bones are within acceptable biomechanical limits.

Disclosures

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