Unlike natural teeth, dental implants do not have a periodontal ligament that acts as a mechanical receptor and absorbs shocks from chewing forces. Therefore, osseointegrated implants are more prone to occlusal overload. Occlusal overload is an etiologic factor of biomechanical complications such as marginal bone loss, prosthetic complications, and implant failure. Therefore, controlling implant occlusion within the physiologic limits and providing optimal implant load are important to ensure implant success. Overloading factors include long cantilevers, inappropriate occlusal designs, poor bone quality, excessive superstructure height, and parafunctions.

Bruxism, an overloading factor, is defined as a parafunctional activity that involves squeezing and grinding teeth during the day or at night. The forces observed during bruxism are more damaging than equivalent masticatory forces. Moreover, they can increase the risk of implant failure and mechanical and technical complications of implant-supported restorations. These negative consequences are due to high occlusal forces and prolonged contact with unstable eccentric components during bruxism. A bruxism treatment plan should reduce the negative impacts of bruxism on bone, implants, and restorations. In this context, increasing the bone-to-implant contact area improves osseointegration and stress distribution. In addition, the number of implants can be increased to reduce the pressure on a single implant. Wider and longer implants increase the success rate. Cantilever length in prostheses should be reduced as much as possible. Furthermore, metal occlusal surfaces reduce the risk of porcelain fracture and do not require substantial abutment reduction, which increases prosthetic retention. The use of night guards can also reduce the impact of stress on implants and restorations.

The concepts of occlusal overload and stress distribution are more prominent in the All-on-4 treatment concept (Nobel Biocare), in which a full-arch fixed prosthesis is supported by only four implants. In the All-on-4 concept, two anterior implants are placed axially, while posterior implants are tilted distally, approximately 30 degrees to the occlusal plane, and anterior implants were placed axially. Bone, implant, and prosthetic components were modeled separately and were tightly connected to each other. Under two distinct loading conditions representing the occlusal forces of healthy and bruxist individuals, the stresses on peri-implant bone, implant, and prosthetic components were evaluated using finite element analysis.

**Effect of Implant Diameter and Bruxism on Biomechanical Performance in Maxillary All-on-4 Treatment: A 3D Finite Element Analysis**

Taygun Sezer, DDS¹/Kerem Kilic, DDS, PhD¹/Emir Esim, PhD²

**Purpose:** To examine the stress distribution in the maxillary All-on-4 treatment concept supported by implants of different diameters under two different loading forces using finite element analysis. **Materials and Methods:** Two distinct All-on-4 designs were prepared in a fully edentulous maxilla, supported by 3.3- and 4.1-mm–diameter implants. Posterior implants were tilted distally, approximately 30 degrees to the occlusal plane, and anterior implants were placed axially. Bone, implant, and prosthetic components were modeled separately and were tightly connected to each other. Under two distinct loading conditions representing the occlusal forces of healthy and bruxist individuals, the stresses on peri-implant bone, implant, and prosthetic components were evaluated using finite element analysis. **Results:** There were higher stresses on cortical bone than on trabecular bone. The stresses on bone and implant components were concentrated around the posterior implants, whereas stresses on the prosthesis were concentrated anteriorly. With increasing implant diameter, the stresses on trabecular bone, abutments, and crowns increased, whereas the stresses on cortical bone, implants, and frameworks decreased. Compressive stresses in the cortical bone and von Mises stresses in the frameworks exceeded the overload limit in both models under bruxist loading. **Conclusion:** The stresses on the cortical bone, implants, and frameworks were slightly higher in the model with 3.3-mm–diameter implants, whereas the stresses on the trabecular bone, abutments, and crowns were slightly higher in the model with 4.1-mm–diameter implants.
two posterior implants are placed with a distal inclination of up to 45 degrees. By tilting the distal implants, a more posterior implant position is achieved; stronger implant anchorage is achieved by using the cortical bone of the maxillary sinus and nasal fossa wall. With this implant arrangement, greater interimplant distance, shorter cantilever length, and a more favorable stress distribution can be achieved. Despite the successful use of the All-on-4 concept in the rehabilitation of full edentulism, restorations supported by narrow-diameter implants may be overloaded, especially in the context of high occlusal forces such as those caused by bruxism. To the authors’ knowledge, there is a lack of literature regarding the biomechanical effect of bruxism-associated overload on the All-on-4 concept. Finite element analysis (FEA) is a widely accepted method for investigating the biomechanical behaviors of structures. The aim of this study was to use FEA to evaluate stress levels and distributions in the maxillary All-on-4 concept supported by 3.3- and 4.1-mm–diameter implants under two distinct loading forces, representing bruxist (B) and healthy (H) individuals. The null hypothesis of the study was that stress distribution on the bone, implant, and prosthetic components is not affected by the diameters of implants or loading forces in the All-on-4 concept.

MATERIALS AND METHODS

In this study, two distinct All-on-4 designs, supported by 3.3 × 10-mm and 4.1 × 10-mm implants (Straumann bone level tapered [BLT], Institut Straumann), were created in a completely edentulous maxilla (Fig 1). In both models, the anterior implants were positioned axially, and the posterior implants were positioned at 30 degrees inclined distally. Four different analyses were performed on each model under two distinct forces representing B and H individuals.

- H1: 3.3-mm implants were used, and occlusal forces of healthy individuals were applied.
- B1: 3.3-mm implants were used, and occlusal forces of bruxist individuals were applied.
- H2: 4.1-mm implants were used, and occlusal forces of healthy individuals were applied.
- B2: 4.1-mm implants were used, and occlusal forces of bruxist individuals were applied.

Modeling

A 3D model of the edentulous maxilla was created from the computed tomography data of a patient meeting the appropriate criteria. Solid modeling of cortical bone (2-mm thickness), trabecular bone, and gingival soft tissue was performed using surface modeling techniques in SolidWorks (SolidWorks) with reference to the maxilla model (Fig 2).

Each implant component (implants, abutments, and screws) used in the study was modeled and adapted individually in accordance with its actual dimensions using SolidWorks (Fig 3). The prosthetic frameworks and crowns were scanned with a 3D optical scanner (Dental Wings 7 Series [Model DW-7-140, Dental Wings]), and the data obtained were transferred to the Geomagic Design X.
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(3D Systems) program in .stl format. Solid models of the scan images were obtained using various solidification methods. The frameworks were modeled as chrome-cobalt alloy, and the crowns were individually modeled as monolithic zirconia with contact points provided. The prosthetic cantilever length was planned as 10 mm. Prosthetic elements, implant elements, and bone tissue made of solid models were combined and adapted according to the following features: The implant platform was placed 1.5 mm below the bone crest, abutments were connected to implants and prosthetic frameworks with titanium screws, gum tissue was formed, and zirconia crowns were connected to frameworks. Thus, cortical bone, trabecular bone, implant elements, and prosthetic elements were transferred to the model with their actual morphology (Fig 4).

Solid models made in the SolidWorks program were transferred to the finite element software program (Ansys Workbench, version 18.1, Ansys), preserving the 3D coordinates. Elasticity modulus and Poisson ratio values were defined for each of the structures whose mathematical models were created with Ansys 18.1 software (Table 1). The mesh with 10-node quadratic tetrahedral elements was created with nodes/elements ranging from 5,085,206/3,133,745 to 5,108,202/3,146,207. In all models, it was assumed that the implants were fully osseointegrated and there was a tight connection between the bone and the implants along the entire interface. In addition, all models were accepted as comprising homogenous, isotropic, and linear elastic materials.

### Boundary and Loading Conditions

Boundaries of the models were constrained at the superior surface of the maxilla to ensure zero displacement, and all structures were modeled as tightly bonded. Occlusal forces were applied bilaterally at an angle of 45 degrees in the palatobuccal direction. For healthy individuals, 100-, 150-, 150-, and 200-N forces were applied to the canines, first and second premolars, and first molars, respectively. For bruxist individuals, 250-, 375-, 375-, and 500-N forces were applied to the same teeth, respectively (Fig 5).

### Analysis

Both von Mises stress values (vM), which provide a global measure of load transfer mechanisms, and principal stress values (minimum principal stress [Pmin] and maximum principal stress [Pmax]) were used to define local risk indicators of peri-implant bone resorption to evaluate trabecular and cortical bone. Peak stress values were considered for evaluation, and the values

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**Table 1 Elastic Modulus and Poisson Ratios**

<table>
<thead>
<tr>
<th></th>
<th>Elastic modulus (MPa)</th>
<th>Poisson ratio</th>
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<tbody>
<tr>
<td>Cortical bone</td>
<td>13,700</td>
<td>0.30</td>
</tr>
<tr>
<td>Trabecular bone</td>
<td>1,370</td>
<td>0.30</td>
</tr>
<tr>
<td>Titanium (implant)</td>
<td>110,000</td>
<td>0.35</td>
</tr>
<tr>
<td>Zirconia</td>
<td>205,000</td>
<td>0.22</td>
</tr>
<tr>
<td>Co-Cr</td>
<td>218,000</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Co-Cr = cobalt-chromium.
Fig 6 Stress values and stress distribution in the trabecular bone. Von Mises stress distribution in (a) H1, (b) B1, (c) H2, and (d) B2. Pmin stress distribution in (e) H1, (f) B1, (g) H2, and (h) B2. Pmax stress distribution in (i) H1, (j) B1, (k) H2, and (l) B2.
were recorded in units of megapascals (MPa). In accordance with similar studies, overloading of the bone was recorded when the Pmax or Pmin exceeded the uniaxial tensile or compressive strength, respectively. The strength of cortical bone was assumed to be 115 MPa under tension and 151 MPa under compression. Implants, abutments, screws, frameworks, and crowns were analyzed based on the vM criterion. Overload was recorded when the peak vM values exceeded the yield strengths of the structures: implants, 576 MPa (3.3-mm diameter) and 785 MPa (4.1-mm diameter); abutments and screws, 508 MPa; framework, 710 MPa for cobalt-chromium dental alloy; and crowns, 3,292 MPa for monolithic zirconia.

The stresses in the bone, implant, and prosthetic components were compared based on the vM criterion, and the results were interpreted in accordance with the principle of fatigue. The maximum vM values in all structures were ranked as trabecular bone < screws < cortical bone < implants < abutments < frameworks < crowns (Tables 2 and 3).

**RESULTS**

Peak stresses were concentrated in the apex area of posterior implants in trabecular bone and in the neck area of posterior implants in cortical bone (Figs 6 and 7). There was higher stress on cortical bone than on trabecular bone. With increasing implant diameter, the stresses on trabecular bone increased and the stresses on cortical bone decreased. Peak Pmin values under bruxist loading exceeded the compressive strength of cortical bone in both models (B1 and B2). In addition, the Pmax value in B1 (114.8 MPa) was at the threshold of the tensile strength of the cortical bone (Table 2).

Peak stresses in implants were concentrated on the neck of posterior implants in the buccal region; accordingly, more stress was detected at the posterior abutment and abutment screws (Fig 8). With increasing implant diameter, the stresses on implants and screws decreased, whereas the stresses on abutments increased. Nevertheless, all stress values on the implant, abutment, and screws were below the yield strengths of the materials (Table 3).

Peak stresses in the frameworks were concentrated around the anterior abutments in the palatal region. High stress levels were also observed in the palatal region of the midline. Peak stresses in the crowns were concentrated in the palatal region at the marginal edge of the crowns on the anterior abutments (Fig 9). With increasing implant diameter, the stresses on frameworks decreased, whereas the stresses on crowns increased. Peak vM values in frameworks under bruxist loading exceeded the yield strengths of the materials for both models (B1 and B2). However, all stress values on crowns were below the yield strengths of the materials (Table 3).

The maximum vM values in all structures were ranked as trabecular bone < screws < cortical bone < implants < abutments < frameworks < crowns (Tables 2 and 3).
Fig. 7 Stress values and stress distribution in the cortical bone. Von Mises stress distribution in (a) H1, (b) B1, (c) H2, and (d) B2. Pmin stress distribution in (e) H1, (f) B1, (g) H2, and (h) B2. Pmax stress distribution in (i) H1, (j) B1, (k) H2, and (l) B2.
DISCUSSION

This FEA study compared the stresses in the maxillary All-on-4 concept supported by 3.3- and 4.1-mm implants under two different loading forces representing bruxist and healthy individuals. The null hypothesis was rejected, as the stress distribution was affected by loading forces and implant diameter.

According to the mechanostat theory, when a physiologic stimulus exceeds the tolerable limit, it can cause bone resorption. Although the threshold for bone resorption is not known, it is presumed that an overload will occur when Pmax and Pmin values exceed the tensile and compressive strengths, respectively. However, the tensile and compressive strength values described in the literature are not specific to the maxilla or mandible but were obtained from the analysis of bones such as the tibia, femur, fibula, and vertebrae. Moreover, while the predetermined overload limit has some merit, the structures/materials involved could also be subject to an overload failure involving fatigue from the repetitive loading encountered in the mouth. For this reason, the overload...
Fig 8  Von Mises stress values and stress distributions on implants, abutments, and abutment screws. Von Mises stress distribution on implants in (a) H1, (b) B1, (c) H2, and (d) B2. Von Mises stress distribution on abutments in (e) H1, (f) B1, (g) H2, and (h) B2. Von Mises stress distribution on screws in (i) H1, (j) B1, (k) H2, and (l) B2.
findings in this study do not indicate that bone loss will occur or that treatment will fail under clinical conditions; however, the risk of bone loss may be reduced when a larger implant is used because stresses on peri-implant cortical bone are reduced. Previous studies examining the effects of implant diameter on stress distribution for the All-on-4 concept support this result.26,36,38 However, unlike the results of previous FEA studies,26,35,36,47 the stresses on trabecular bone increased slightly with increasing implant diameter in the present study. This discrepancy may be due to differences in loading conditions and modeling.

Because the elastic modulus of cortical bone is higher than the elastic modulus of trabecular bone, the chewing forces are maximally transferred to the cortical bone nearest the top of the implant threads,38 and the greatest risk of bone resorption occurs in this region.47 In addition, the biomechanical response of the All-on-4 concept is sensitive to the area on which the load is applied, and the loading of distal cantilevers causes excessive stress around the inclined posterior implants.36 The concentration of peak stresses in cortical bone around the posterior implants in this study supports these findings. Under bruxist loading, compressive stresses in cortical bone in both models (B1 and B2) exceeded the overload limit and the tensile stress in B1 was at the overload limit, which might be especially important in the posterior maxilla that exhibits thin cortical bone.36,48

Static loading test studies have shown that the implant failure resistance increases with increasing implant diameter.27,39 Additionally, previous FEA studies have found that stress on the implants decreases with increasing implant diameter.38,47,49 In the present study, in accordance with current and previous findings, more stress was encountered in smaller-diameter implants. Although the peak stress on the abutments increased slightly with increasing implant diameter, the results showed that preferable stress was provided in implants and screws with larger-diameter implants. Regardless of bruxist loading, the peak stresses were below the yield strengths of the materials, indicating that both 3.3- and 4.1-mm–diameter implants were successful under the conditions analyzed. However, it should be considered that the torquing process that clinically causes pre-stresses on screws and abutments cannot be simulated by an FEA study.

Bruxism is a risk factor for mechanical complications13 and ceramic fractures,50 and technical interventions are generally required in implant-supported restorations.51–53 Previous studies showed that bruxism is the primary cause of prosthetic complications occurring in the maxillary All-on-4 concept.21,28,54 In this study, the peak stresses in frameworks exceeding the yield strength of the material under bruxist loading indicate a risk of mechanical complications. The high stress values in crowns suggested the possibility...
Fig 9  Von Mises stress values in the frameworks and crowns. Von Mises stress distribution on frameworks in (a) H1, (b) B1, (c) H2, and (d) B2. Von Mises stress distribution on crowns in (e) H1, (f) B1, (g) H2, and (h) B2.
of ceramic fracture and chipping, especially under high chewing forces.

Distinct loading conditions were used in the FEA. However, because the stress distribution is substantially affected by the loading conditions, determining the loading conditions appropriate for the clinical conditions is essential for obtaining realistic results. Oblique loads were used in the present study because they reflect the occlusal directions more realistically and cause greater stress on cortical bone. Occlusal force and muscle activity measurement studies in the literature were used to determine the reference force magnitude. The maximum occlusal force recorded in the molar region in healthy individuals ranges from 120 to 600 N. Bakke reported that the occlusal force in the anterior teeth is 70% in the premolar region and 40% in the molar region. Patients rehabilitated with the All-on-4 treatment concept have a similar muscle surface electromyography contraction pattern to patients with natural dentition. Based on this information and previous FEA studies, occlusal forces of healthy individuals were determined. For bruxist loading, a 2.5-fold greater force than that of healthy individuals was applied. However, published literature indicates that the relationship between high occlusal force and bruxism is controversial. Some studies have reported that bruxism causes an increase in muscle strength, such that forces present during bruxism exceed the occlusal forces during chewing.

However, Cosme et al (2005) found no difference in maximum occlusal force between bruxist and nonbruxist individuals. These differing results are reasonable when considering the differences in bruxism criteria included in the studies, differences in measurement methods, and changes in bruxism intensity at measurement times. The effect of the loading period should also be considered when evaluating the results. Prolonged contact with unstable eccentric components during bruxism is more destructive than equivalent masticatory forces. The inability to measure this effect with FEA is one of the limitations of this study.

Finite element analysis has well-known inherent limitations, such as boundary and loading conditions, material properties, and the assumption that most variables are constant. In the present study, all materials were regarded as homogenous, isotropic, and linear elastic, as in previous FEA studies. However, bone tissue, which is a living tissue, does not show homogeneity in terms of density and structure; moreover, it is not isotropic. Although histologic studies in the literature have stated that bone-to-implant contact varies between 30% and 70%, bone-to-implant contact in the present study was regarded as 100%, in accordance with previous studies. In addition, modeling of the alveolar part of the maxilla alone (ie, without sinuses) and modeling of the cortical bone as uniformly 2 mm were other limitations of this study. Thus, in the All-on-4 concept, the effect of implant diameter on stress distribution under high occlusal forces should be investigated with further studies using different jaw models, and the results should be supported by in vivo and clinical studies.

CONCLUSIONS

Within the limitations of this study, the following conclusions were reached:

1. Peak stresses on trabecular bone, abutments, and crowns increased with increasing implant diameter, whereas peak stresses on cortical bone, implants, and frameworks decreased.

2. For both models, compressive stresses in cortical bone and stresses in the frameworks exceeded the overload limit under bruxist loading. Except for these, stress values in the bone tissue, implant, and prosthetic components were below the overload limit.

3. The 4.1-mm–diameter implants created lower stress on the cortical bone, implants, and frameworks, whereas they created higher stress on trabecular bone, abutments, and crowns compared with 3.3-mm–diameter implants. The small difference in the results suggested that 3.3-mm–diameter implants could be an alternative to augmentation procedures in the maxilla when there is insufficient bone width for larger-diameter implant placement.

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REFERENCES


