The atrophic maxilla presents some challenges in conventional osseointegrated implant placement.1,2 In particular, in the posterior region, vertical and/or horizontal residual bone height (RBH) insufficiency occurs due to maxillary sinus enlargement.2 Sinus elevation or tilted implant techniques are alternative therapeutic approaches for implant rehabilitation of the atrophic edentulous maxilla. In addition, zygomatic implants are now used more frequently in the treatment of severe bone deficiencies and can be placed without major grafting procedures.1,3

Although the main purpose of these techniques is to provide dental implant placement and prosthetic rehabilitation in insufficient maxillary bone, each technique has different protocols. Insufficient vertical bone height in the posterior maxilla can be increased by sinus elevation procedures.4,5 This technique is generally divided into two categories: direct or indirect technique. The direct technique or lateral window technique can be performed as a single-stage surgery (4 to 6 mm RBH) or in two stages (1 to 3 mm RBH). The indirect or internal elevation technique is less invasive (< 6 mm RBH).5 On the other hand, avoiding implant placement in the reduced posterior bone height may be an option. This procedure is called the All-on-4 treatment concept (Nobel Biocare) and supports four implants, fixed or provisional prostheses, placed in the anterior region of edentulous arches. Two implants are placed vertically in the anterior region and two implants are placed distally inclined to avoid maxillary sinus perforation in the posterior region.6 An alternative graftless solution to atrophic maxilla treatment is zygomatic implants, which are much longer than traditional dental implants and pass the crestal bone and the maxillary sinus (intrasinus or extrasinus position) to engage the zygomatic bone and use them for anchorage to retain a dental prosthesis.7,8

Finite element analysis (FEA) is a technique that allows problem-solving by limiting the material

**Purpose:** To determine the von Mises stress values of extramaxillary implants anchored in zygomatic bone, known as zygomatic implants, abutments, superstructures, and principal stress values of bone under occlusal forces and to compare them with tilted implants and sinus elevation concepts. The hypothesis of the study was that there would be higher stress on zygomatic implants under occlusal forces compared with tilted implants and the sinus elevation technique due to the more angled placement of the zygomatic implants. **Materials and Methods:** Finite element analysis (FEA) was used to apply a force of 600 N (75 N premolars and 150 N first molar) vertically and at an angle of 20 degrees to the hybrid prosthesis with three different concepts—zygomatic implants, tilted implants, and sinus elevation—in D2 bones in six separate models. The posterior implants were tilted in zygomatic implant models (45 degrees) and tilted implant models (30 degrees). The von Mises and principal stress values formed in the models were compared by FEA. These values were also compared with the physiologic stress limit of the bone. **Results:** In the zygomatic implant models, the von Mises stress values on both anterior and posterior implants were less than other models under both loading conditions. In addition, the lowest principal stress values were seen in these models. The highest von Mises stress among all models was found to be posterior implants in tilted implant models under oblique loading. In addition, the highest principal stress values were seen at posterior implants in the sinus elevation model under oblique loading. Vertical loading was found to induce less stress than loading at a 30-degree angle. **Conclusion:** Although zygomatic implants have a more angled placement, the stress values on the bone and implants are lower. Int J Oral Maxillofac Implants 2022;37:563–570. doi: 10.11607/jomi.9631

**Keywords:** finite element analysis, sinus elevation, tilted implant, zygomatic implant

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consisting of infinite points to countable points, and it is a powerful method for calculating the displacements, stresses, and strains by solving individual elements. It has been widely used in dentistry to evaluate the stress analysis of implants, bones, and superstructures.

There are several publications in the literature evaluating stress analysis on zygomatic implants by the FEA method. In these studies, bone defects—obturator prosthesis, craniofacial structures on stress distribution, and effects of zygomatic implant techniques were evaluated. However, there is no study comparing it with other techniques used in the atrophic maxilla for implant rehabilitation. In this study, stress distribution under occlusal force was evaluated by FEA in zygomatic implant, tilted implant, and sinus elevation models. The hypothesis of the study was that there would be more stress on the zygomatic implants under occlusal forces compared with tilted implants and the sinus elevation technique due to the more tilted placement of the zygomatic implants. The aim of this study was to determine the stress values of zygomatic implant models and superstructures under different occlusal forces and to compare them with tilted implant and sinus elevation models.

**MATERIALS AND METHODS**

**FEA Models**

The simulations were divided into six models according to treatment planning concepts (Figs 1a: zygomatic, 1b: sinus elevation, and 1c: tilted) and loading. These models were as follows: model 1: zygomatic implants, vertical loading; model 2: tilted implants, vertical loading; model 3: sinus elevation concepts, vertical loading; model 4: zygomatic implants, oblique loading; model 5: tilted implants, oblique loading; and model 6: sinus elevation concepts, oblique loading.

**Modeling of Maxilla, Dental Implants, and Superstructure**

Edentulous adult cadaver tomography was used to create an edentulous atrophic maxilla bone model. Tomography data were reconstructed with a slice thickness of 0.1 mm. The tomography data obtained as a result of the reconstruction were transferred to the 3D Slicer software in DICOM (.dcm) format. CT data in DICOM format were parsed according to the appropriate Hounsfield values in 3D Slicer software and transformed into a 3D model by a segmentation process. The model was exported in .stl format. The 3D model was transferred to the Altair Evolve software, where the appropriate atrophic maxilla cortical geometry was modeled. Cortical bone thickness was adjusted to be 0.7 mm in the anterior region (up to the canine tooth area) and 1 mm in the posterior region. The trabecular bone was obtained by referring to the inner surface of the 3D maxilla cortical bone, whose thickness was adjusted.

Nobel Parallel Conical Connection TiUltra implants (7, 10, and 13 mm long and 4.3 mm in diameter), Nobel Biocare Bränemark System Zygoma implant (45 mm long and 4.4 mm in diameter), and Multi-unit Abutment Xeal abutments (3.5 mm long, straight and angled 30 degrees) used in the study were modeled in Altair Evolve software. Prosthetic parts (metal substructure and prosthesis) were modeled in Altair Evolve software. The hybrid prosthesis was modeled as a superstructure model. Dimensions specified in Wheeler’s tooth anatomy were used in teeth modeling. Altair HyperMesh software was harmonized between mesh structures to provide force transfer between models.

In all models, anterior implants were placed in lateral regions, and posterior implants were placed in second premolar regions (Fig 1). Anterior implants were placed in the middle, and posterior implants were placed at the palatal margin of the alveolar bone (near 1 mm). Zygomatic implants were applied with the “in the wall of the maxilla” technique following the ZAGA recommendations. Anterior implants were 10 mm in length and 4.3 mm in diameter and placed vertically in all models. The posterior implants in zygomatic implant models were 35 × 4.4 mm in size and tilted at 45 degrees (Fig 1a). In tilted implant models, the posterior implants were 13 × 4.3 mm in size and tilted 30 degrees (Fig 1b). The angles of the posterior implants in the zygomatic implant models and the tilted implant models were different because the prosthetic structures were supported from the second premolar region in all models. In sinus elevation models, posterior implants were 7 × 4.3 mm in size and placed vertically (Fig 1c). The 30-degree tilted abutments were used on posterior implants in tilted implant models. All prepared models were placed in the correct coordinates in 3D space in Altair Evolve software, and the modeling process was completed.

FREEZE-type contact definition was made in all areas with contact in all study models (cortical-trabecular bone interface, implant-bone contact area, implant-abutment and screw connections, and abutment-screw-bar contact surfaces). This approach is based on the assumption that the parts move with full correlation during their motion.

**Analysis**

Mathematical models were formed by dividing geometric models into simple and small pieces called meshes. After the modeling process was completed in the Altair Evolve software, the models were mathematically created with the Altair HyperMesh software and made ready for analysis. For analysis, models prepared in Altair HyperMesh software were transferred to the Altair OptiStruct analysis program in .fem format.
Material Properties
In the analysis, the linear material properties of the materials with elastic modulus and Poisson ratio were used (Fig 2). The material properties of the analyzed model were defined numerically and visually.

Boundary Conditions and Loading
There were two types of loading scenarios for three models, vertical and oblique, and a total of six analyses were performed. The loading was applied as 75 N on the premolar teeth and 150 N on the first molar tooth. Vertical loading was applied from the fossa of the teeth perpendicular to the occlusal plane (Fig 3a), and oblique loading was applied from the lingual cusp of the teeth at an angle of 20 degrees in the buccolingual direction (Fig 3b). By distributing the loading definitions to the nodal points in the application regions, stress singularity in the relevant regions is prevented.

The models are fixed by restricting all degrees of freedom from the nodal points in the upper part of the cortical bone so that movement in all three axes is prevented. In all parts of the model, the boundary condition was applied to be symmetric with respect to the Y-Z plane on the normal of the x-axis (Fig 3c).

Total of Nodes and Elements
Information for the three different analysis models created is shared in Table 1.

![Fig 1](a) Zygoma, (b) tilted implant, and (c) sinus elevation models used in FEA. The implants are placed in the lateral and second premolar regions.

<table>
<thead>
<tr>
<th>Material</th>
<th>Color</th>
<th>Young modulus*</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium implant</td>
<td>Purple</td>
<td>103,400</td>
<td>0.35</td>
</tr>
<tr>
<td>Titanium (abutment and screw)</td>
<td>Yellow</td>
<td>110,000</td>
<td>0.28</td>
</tr>
<tr>
<td>Bar (Cr-Ni)</td>
<td>Orange</td>
<td>200,000</td>
<td>0.33</td>
</tr>
<tr>
<td>Prosthesis (acrylic)</td>
<td>Red</td>
<td>3,000</td>
<td>0.35</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>Brown</td>
<td>13,700</td>
<td>0.3</td>
</tr>
<tr>
<td>D3 cancellous bone</td>
<td>Green</td>
<td>1,370</td>
<td>0.3</td>
</tr>
</tbody>
</table>

![Fig 2](Young Modulus (MPa*) and Poisson ratio values used for the analyses.)

![Fig 3](Crows were loaded at 75 N (premolars) and 150 N (first molar) (a) vertically and (b) at a 20-degree angle. (c) Boundary conditions where the skull is fixed are highlighted in red.)

<table>
<thead>
<tr>
<th>Model</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of nodes</td>
<td>962,715</td>
<td>660,586</td>
<td>671,461</td>
</tr>
<tr>
<td>Total no. of elements</td>
<td>3,881,423</td>
<td>2,630,512</td>
<td>2,687,011</td>
</tr>
</tbody>
</table>

Model 1 = zygomatic implant; model 2 = tilted implant; model 3 = sinus elevation.
RESULTS

Von Mises Values in Implants, Abutments, Screws, and Prostheses

Von Mises stress values on both anterior and posterior implants in model 1 were less than in models 2 and 3 under both loading conditions (Figs 4a1, 4a4, 4b1, and 4b4 and Table 2). The highest von Mises stress values among all models were found to be in posterior implants in model 2 under oblique loading (Figs 4b5 and Table 2). The highest von Mises stress values on the abutments and screws occurred in model 2 in both loading conditions (Figs 4c2, 4d2, 4c5, and 4d5 and Table 2). In model 3, von Mises stress values of the abutments were lower than other models under both loading conditions (Figs 4c3, 4d3, 4c6, and 4d6 and Table 2). Von Mises stress values in the prosthesis were higher in the posterior region; the von Mises stress values in the distal side of the bar and abutment junction were highest in all models and under both loading conditions (Fig 4e and Table 2). In addition, higher stress values were observed in all models under oblique loading conditions compared with vertical loading (Table 2).

Minimum and Maximum Principal Stress Values in Bone Around the Implant

Among all simulations, the lowest principal stress values were observed in the anterior implants of model 1 under vertical loading conditions (Figs 5a1, 5b1, 5c1, and 5d1 and Table 3). In addition, the highest principal stress values were seen at posterior implants in model 3 under oblique loading (Figs 5a6, 5b6, 5c6, and 5d6 and Table 3). Among the implants in the posterior region, the lowest principal stress values were seen in model 1 (Table 3).
It was observed that the maximum principal stress values were higher in the cortical bone in the anterior region (Figs 5a and 5c) and the minimum principal stress values were higher in the posterior region (Figs 5b and 5c and Table 3). Also, principal stress values were found to be higher in the posterior region in cancellous bone compared with the anterior region (Table 3).

**DISCUSSION**

Although there are many FEA studies relating to zygomatic implants, it has not been compared with other procedures applied to the atrophic maxilla, such as tilted implants and sinus elevation. In the present study, these three concepts were compared with FEA under two different loading conditions. The hypothesis that stress values were higher in zygomatic implants due to more inclined placement was rejected. As a result of the study, the stress values in the implant, bone, and prosthesis were lower in the zygomatic models compared with the other models (Figs 4 and 5 and Tables 3 and 4). In addition, the von Mises values of the abutment and screw were highest in the tilted implant models and lowest in the sinus elevation models.

In the literature, the applied force and implant placement may be different in FEA studies. Also, the force was applied to the implant, abutment, or prosthetic structures at 20, 30, 45, 60, or 75 degrees.9,14,15 In studies where the prosthetic superstructure is loaded, loading was made assuming that the occlusal force contact in the maxillary region is from the posterior tooth fossa and cusps.2,15–17 It was stated in the literature that the maximum occlusal force in adult patients is between 500 and 700 N.18,19 In addition, Boven et al20 stated that the occlusal force decreased in edentulous patients but increased after implant-supported prosthesis rehabilitation. Similar to these studies, vertical loading was applied from the fossa, and oblique (20-degree) loading was applied to the lingual cusp with a 20-degree angle of the premolars (75 N) and first molar (150 N) teeth in the present study (Fig 3).

![Figure 5](image-url)  
**Figure 5** Columns represent both loading conditions of model 1 (1, 4), model 2 (2, 5), and model 3 (3, 6). Rows represent the following: (a) maximum principal stress values of cortical bone, (b) minimum principal stress values of cortical bone, (c) maximum principal stress values of cancellous bone, and (d) minimum principal stress values of cancellous bone. Red indicates areas of increased stress. V = vertical loading; O = oblique loading.

**Table 3 Principal Stress Values in Models (MPa)**

<table>
<thead>
<tr>
<th></th>
<th>Vertical loading</th>
<th>Oblique loading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td><strong>Cortical bone</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Max P</td>
<td>7.0</td>
<td>27.8</td>
</tr>
<tr>
<td>A. Min P</td>
<td>4.4</td>
<td>16.6</td>
</tr>
<tr>
<td>P. Max P</td>
<td>0.8</td>
<td>4.8</td>
</tr>
<tr>
<td>P. Min P</td>
<td>46.7</td>
<td>75.2</td>
</tr>
<tr>
<td><strong>Cancellous bone</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Max P</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>A. Min P</td>
<td>0.7</td>
<td>3.0</td>
</tr>
<tr>
<td>P. Max P</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>P. Min P</td>
<td>3.5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Model 1 = zygomatic implant; model 2 = tilted implant; model 3 = sinus elevation. Maximum principal stress values define tensile stress and minimum principal stress values define compressive stress.
Comparison of von Mises and Principal Stress Values in Three Different Models

In model 1, the von Mises stress values and principal stress values on both anterior and posterior implants/regions were less than models 2 and 3 in both loading conditions (Tables 2 and 3). This may be due to the use of zygomatic implants bicortically. Verri et al. described that bicorticalization techniques have biomechanical advantages because they reduce stress distribution in bone tissue and materials. These techniques offered the possibility of transmission of stress to the upper cortical bone (in the zygomatic bone) with the increase of the cortical contact area where the stress mainly occurs, and of distributing the stress transferred by occlusal loading. In addition, these techniques can be used to ensure primary stability of the implant on the bone tissue for the maxillary region in fresh sockets or low-density bones.

The inclined implant placement increases the stress values in the bone, prosthetic structure, and implant, as the direction of occlusal loads is not parallel to the long axis of the implant. Duan et al. stated that as the inclination of the zygomatic implants increases, larger lateral force and bending moments occur, so the stress on the bone and the implant increases. However, although the zygomatic implants were more inclined than the posterior implants in all models, there were lower von Mises and principal stress values in the present study. Ozan and Kurtulmus-Yilmaz, in their study comparing the angle of implants with cantilever lengths, reported that cantilever lengths are more effective in stress formation. Correa et al. described that the cantilever length is safe up to 10 mm in terms of stress distribution in fixed prostheses supported by four implants. The present study used fixed prostheses in all models, and cantilever lengths were < 10 mm. The increase in the force arm increases the stress that will occur. The length of the force arm may vary depending on whether the implant is tilted distally (tilted implant models) or medially (zygomatic implant models). The occlusal force may cause more bending force because force is outside the rests of the implants, so more von Mises stress values may have occurred in distal tilted implants (Fig 6). However, comparisons regarding stress formation in the cantilever region of distal and mesial tilted implants are insufficient in the literature. Although the principal stress values in posterior and anterior regions in the zygomatic implant models are lower than other models, such planning may cause bone resorption in the future.

In model 2, the distal side of the bar and posterior abutment junction of von Mises stress values were highest in all models and under both loading conditions (Table 2). The highest von Mises stress values were found to be 391 MPa in the prosthesis bar. According to Baran, the yield strength of Ni-Cr alloy was approximately 44,700 MPa to 124,000 MPa, and the tensile strength of Ni-Cr alloy was approximately 65,000 MPa to 165,000 MPa. The use of noble metal alloys under high tensile stresses allows the prosthetic structure to be thinner. The von Mises values of the Ni-Cr alloy bar under these loading conditions do not exceed the yield strength and tensile strength limit. The highest von Mises stress values were found in the posterior abutment, 305.7 N/mm² in model 2. Sadrimanesh et al. in their study on the angles of abutments, reported that the increase in angles causes stress increases in the abutment, implant, and bone. These stress values may have been higher due to the tilted abutments in model 2. The yield strength of titanium was 110,000 MPa in the literature. In the present study, the von Mises values of the titanium implants and abutments do not exceed this limit. However, metal fractures occur primarily as a result of weakening of metal due to cyclic loading, resulting in an accumulation of small cracks, so the application of force cycles may be carried out in future studies. Also, clinical and experimental studies described that the stress values are responsible for bone destruction. According to the Harold Frost Mechanostat theory, bone resorption is observed in the bone-to-implant contact area under a load of 67 N/mm². Sugiura et al. described that bone resorption begins at 50 N/mm², while Greenstein et al. stated that the physiologic stress limit of the bone is 40 N/mm². In the present study, the minimum principal stress values of the cortical bone in the posterior region exceeded 40 N/mm² under both loading conditions. Although the principal stress values in posterior and anterior implants in the zygomatic implant model
are lower than in other models, such planning may cause bone resorption.

Almeida et al.\(^ {17} \) stated that the use of short implants will increase stress in the bone. Similarly, Lofaj et al.\(^ {15} \) described that shortening of the implant and insufficient cortical bone increase compressive stresses. In the present study, posterior implants in sinus elevation models were 7 mm (shortest among all models), and the minimum principal stress values were highest in this region. In addition, the minimum principal stress values in the posterior region and the maximum principal stress values in the anterior region were higher in all models because the force was applied to the premolar and molar regions. Also, Sivrikaya and Omezli\(^ {16} \) stated that implant design and bone density are also effective in stress distribution. According to the Lekholm and Zarb classification, D2 and D3 bone are the most suitable bones for implant placement.\(^ {14,16} \) In addition, it is stated that implant designs and bone density are also effective in stress distribution. According to the Lekholm and Zarb classification, D2 and D3 bone are the most suitable bones for implant placement.\(^ {14,16} \) In addition, it is stated that the main stress distribution occurs in cortical bone according to cancellous bone.\(^ {14} \) In addition, atrophic skull models were used in zygomatic implant studies generally, as in the present study.\(^ {1,3,8} \) Gümrükçü\(^ {11} \) modeled the skull bone as D2 and D3. In the present study, D2 bone was used in all models. However, in the fully edentulous atrophic maxilla, D3 and D4 bone may also be present in the zygoma region.

**FEA and Limitations**

In this study, all models had homogenous, isotropic, and linear flexibility, unlike in vivo tissues.\(^ {42} \) While modeling, soft tissues such as muscle and mucosa were not considered. Additionally, implant–bone osseointegration has been simulated as 100%, but this is not possible under clinical conditions.\(^ {42-44} \) However, it has been stated that the results of FEA studies are similar to those of in vivo studies.\(^ {65,46} \) Also, the diameter of the zygomatic implants used in this study were 0.1 mm, much larger than the standard implants, because the brand does not have implants of the same diameter. In the zygomatic model, the alveolar crest is not completely resorbed to ensure standardization with other models.

**CONCLUSIONS**

The best biomechanical outcomes were achieved with zygomatic implants in atrophic maxilla rehabilitation, although they had more angled placement. In addition, tilted abutments in tilted implant models caused higher von Mises stress values. Therefore, implant and prosthetic planning is recommended considering that the occlusal force will create the highest stress in angled abutments in clinical practice.

**ACKNOWLEDGMENTS**

The authors reported no conflicts of interest related to this study.

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