The aim of this in-silico study was to compare stress distributions in implants and zirconia frameworks of mandibular and maxillary implant-supported crowns. For comparison, vertical and oblique loading forces were used. Three-dimensional finite-element implant models of a mandibular section of bone (D2) and a maxillary section of bone (D4) with missing second molars and their zirconium-based superstructures were used. Zimmer dental implants of 13 mm in length and 4.7 mm in diameter were modelled. A load of 200 N was applied toward vertical and oblique (30° to the vertical) directions. Maximum and minimum von Mises stress values of the implants and the zirconia framework were calculated. The highest stress value was concentrated in the zirconia framework of the maxillary implant-supported model with the oblique loading force (301.17 MPa). The lowest stress value was concentrated in the mandibular implant-supported model. And the stress values in the maxilla were higher than in the mandible. The maxilla (D4) showed higher stress values than in the mandible (D2), because the trabecular bone is weaker and less resistant to deformation than the cortical bone. Stress values with oblique loading forces were higher than with vertical loading forces. Because of the high Young’s modulus of zirconia (low elastic properties), zirconia frameworks showed higher stress values than the implants.

**Keywords:** finite element analysis (FEA); stress distribution; zirconia framework; bone quality; vertical and oblique loading force
colour stability and aesthetics than other all-ceramic cores. Additionally, oxide ceramics generally exhibit high biocompatibility with low bacterial surface adhesion and reduced thermal conductivity.\cite{10,12}

The flexural strength of Y-TZP is over 1000 MPa, its fracture toughness is up to 10 MPa/m$^{0.5}$ (fracture toughness unit) and its Young’s modulus value is $\approx$210 GPa, making Y-TZP suitable for all all-ceramic bridges, even those in the posterior region requiring a high degree of strength.\cite{10,13} Because their successful use depends on the stress applied and the physical properties of the materials used, dental materials must be evaluated under compressive loading to determine their fatigue strength. Three-dimensional (3D) finite-element (FE) analysis has been used extensively in dental biomechanical studies to produce detailed and animate or inanimate structures.\cite{14–20} The von Mises stress is a combination of normal and shear stresses occurring in all directions. This stress is important in examining restorative materials and tooth tissue damage that may occur.\cite{21}

The aim of this study was to compare the stress values in implants and zirconia frameworks of mandibular and maxillary implant-supported crowns.

**Materials and methods**

In this in-silico study, 3D FE models of maxillary and mandibular sections of bone with a missing second molar tooth were created. 3D tetrahedral structural solid models were used to create the bone, implant (implant body + abutment), framework and occlusal surface materials (Figure 1). The maxillary bone was modelled as a cancellous core D4 bone surrounded by a 1-mm-thick cortical layer in the upper part. The mandibular bone was modelled as a cancellous core D2 bone surrounded by a 2-mm-thick cortical layer in the upper part. The crowns consisted of framework material and porcelain. The length and diameter of the crowns were 8 and 6 mm, respectively. Two solid 4.7 $\times$ 13 mm screw-type dental implant systems (Zimmer Dental, Carlsbad, CA) were selected for

![Figure 1. Maxilla and mandible, implant-supported crown, implant body and abutment model.](image-url)
this study. The frameworks were developed according to the manufacturer’s instructions on Y-TZP coping (NobelProcera, NobelBiocare AB, Goteborg, Sweden). The design of the frameworks respects the anatomical form of the final restoration, with an occlusal veneering thickness of 1–2 mm. The frameworks were customized with a minimum thickness of 0.8 mm. Feldspathic porcelain (Ceramco II, Dentsply, Burlington, NJ) was used for the occlusal surfaces.

Table 1 lists the Young’s modules and Poisson ratios of cortical bone (D2),

\[ \text{Table 1. Poisson ratio and Young’s modulus values of materials used in the study.} \]

| Material                        | Poisson ratio | Young’s modulus (GPa) |
|---------------------------------|---------------|-----------------------|
| Cortical bone (D2)              | 0.3           | 13.7                  |
| Spongious bone (D4)             | 0.3           | 1.10                  |
| Titanium (implant body + abutment) | 0.34       | 114                   |
| Zirconia                        | 0.33          | 210                   |
| Porcelain                       | 0.35          | 82.8                  |
| Cement                          | 0.35          | 12                    |

stress of all parts of the structure are calculated.[1,28] 3D FE analyses are preferred to 2D techniques because they present an actual representation of stress behaviours on the supporting bone.[2,29]

In our study, maximum and minimum von Mises stress values of the implants and zirconia frameworks of mandibular and maxillary implant-supported crowns were compared under the vertical and oblique occlusal loading forces. When making comparisons, maximum stress values were checked. In this way, eight models were created and each was compared with the others according to the maximum and minimum stresses.

**Stress analysis of the mandibular (D2 bone quality) implant-supported crown**

Figure 2 presents the stress distribution within the implant and zirconia framework for the mandible. For both loading forces, maximum stresses were concentrated at the neck of the implant; however, minimum stresses were concentrated at the root apex of the implant. Moreover, while the maximum stress values for the zirconia frameworks were concentrated around the gingival area for both loading forces, minimum stresses were concentrated at the occlusal area of the zirconia frameworks. Maximum stresses were: 58.64 MPa for the implant with vertical loading, 263.51 MPa for the implant with oblique loading, 61.58 MPa for the zirconia framework with vertical loading and 212.73 MPa for the zirconia framework with oblique loading.

**Stress analysis of the maxillary (D4 bone quality) implant-supported crown**

Figure 3 presents the stress distribution within the implant and zirconia framework for the maxilla. For the vertical loading force, while maximum stresses were concentrated at the root apex of the implant, minimum stresses were concentrated at the neck; however, for oblique loading, while maximum stresses were concentrated at the neck of the implant, minimum stresses were concentrated at the root apex. Moreover, while the maximum stress values for the zirconia frameworks were concentrated around the gingival area for both loading forces, minimum stresses were concentrated at the occlusal area of the zirconia frameworks. Maximum stresses were: 81.48 MPa for the implant with vertical loading, 263.51 MPa for the implant with oblique loading, 51.28 MPa for the zirconia framework with vertical loading and 212.73 MPa for the zirconia framework with oblique loading.
framework with vertical loading, and 301.17 MPa for the zirconia framework with oblique loading.

When the two groups were examined, the highest stress values were concentrated in the maxillary implant-supported model with the oblique loading force. The highest stress value was concentrated in the zirconia framework of the maxillary implant-supported model with the oblique loading force (301.17 MPa) (Figure 3). The lowest stress values were concentrated in the mandibular implant-supported model.

These results suggest that the stress values with the oblique loading forces were higher than those with the vertical loading forces for both the implants and zirconia frameworks of the two groups. Also, the stress values in the maxilla were higher than those in the mandible. Moreover, the zirconia frameworks showed higher stress values than the implants (Table 2).

**Final remarks**

Since the values obtained by FE stress analysis are variances that occur as a result of non-mathematical calculations, no statistical analysis was performed. The aim of
Table 2. Maximum and minimum stress values after force application (MPa).

| Model                                      | Vertical loading | Oblique loading |
|--------------------------------------------|------------------|-----------------|
|                                            | (max.) | (min.) | (max.) | (min.) |
| Mandibular implant-supported crown model   |         |        |         |        |
| Implant                                   | 58.64   | 1.45   | 223.51  | 0.59   |
| Zirconia framework                         | 61.58   | 3.09   | 212.73  | 1.01   |
| Maxillary implant-supported crown model    |         |        |         |        |
| Implant                                   | 81.48   | 3.74   | 263.51  | 1.01   |
| Zirconia framework                         | 51.28   | 3.98   | 301.17  | 3.85   |

Figure 3. Stress analysis of the maxillary implant-supported crown.
this study was rather to review and analyse the values and stress distributions.

When FE analysis is applied to dental implants, it is important to consider oblique occlusal forces because the stress results will be more realistic in the structures, compared with only a vertical occlusal force.[1,30] Papavasiliou et al. [31] showed that oblique loads could increase stresses 10-fold. Similarly, the results of the present study indicated that oblique loading forces caused the highest maximum stress values for both implants and zirconia frameworks.

Zarb and Schmitt [32] stated that bone structure was the most important factor in selecting the most favourable treatment outcome in implant dentistry. Using a 3D FE analysis technique, Sevimay et al. [23] investigated the effects of bone quality on the stress distribution in an implant and implant-supported crown. They showed the presence of lower stresses with D1 and D2 bone qualities and increased stresses for D3 and D4 bone qualities because trabecular bone was weaker and less resistant to deformation.[1,23] Thicker cortical bone (D2) reduces stress concentration around the implants.[33,34] The results of the present study are consistent with the studies above in terms of stress values being greater with trabecular bone (D4) than with cortical bone (D2).

Y-TZP has a high tensile strength (900—1200 MPa) and high Young’s modulus (210,000 MPa). The Young’s modulus of Y-TZP is higher than that of all dental alloys. Indeed, zirconia has a higher Young’s modulus than titanium. In our study, the zirconia framework showed higher maximum stress values than the implant. The zirconia framework used in the present study was also used by Sannino et al. [10], who found that maximum von Mises stress values were concentrated around the gingival area of the Y-TZP frameworks. Similarly, in our study, the maximum stress values were concentrated around the gingival area of the zirconia frameworks. Sannino et al. [10] stated that the Y-TZP framework reduced the maximal and effective stresses. The much higher Young’s modulus of Y-TZP allowed a more uniform distribution of stress within the framework, providing more efficient and durable load transfer.

When loading vertical and oblique forces to the maxillary implant-supported crown, respectively, von Mises stresses were concentrated at the different points of the implant (Figure 3). For vertical loading, stresses were concentrated at the root apex of the implant; however, for oblique loading, stresses were concentrated at the neck of the implant. Therefore, we conclude that vertical forces are transmitted through the implant in the maxilla more effectively than are oblique forces. Thus, oblique forces may be more harmful to implants.[31]

Further in vitro studies, such as stress distribution analysis, laboratory experiments and clinical studies, need to be conducted to determine stress distributions in different bone qualities of single and multi-unit fixed implant-supported prosthesis with different implant angles.

Conclusions
Within the limitations of this study and based on the results obtained, stress values in the maxilla (D4) were higher than in the mandible (D2), because trabecular bone is weaker and less resistant to deformation than cortical bone. Stress values with oblique loading forces were higher than with vertical loading forces for both the implants and the zirconia frameworks. Zirconia frameworks showed higher stress values than the implants because of the high Young’s modulus of zirconia. Vertical forces are transmitted through the implant in the maxilla more effectively than are oblique forces.

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Disclosure statement
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