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# Biomechanical comparison of four treatment models for the totally edentulous maxilla: a finite element analysis

## Comparação biomecânica de quatro modelos de tratamento para a maxila atrófica totalmente edêntula: análise de elementos finitos

## Comparación biomecánica de cuatro modelos de tratamiento para el maxilar superior atrófico totalmente desdentado: análisis de elementos finitos

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**Abstract**
The aim of this study is to evaluate by finite element analysis different techniques of totally edentulous maxilla rehabilitation, considering implants, bone tissue, metallic infra-structure, and prosthetic abutments characteristics, by means of a three-dimensional model. Stress distribution on bone tissue, implants, and abutments was analyzed with four configurations (six implants axially installed, all-on-four technique, M-4 technique, and four conventional implants with two zygomatic implants). Greater tension on bone tissue were found around distal implants, in all treatment groups, but not exceeding resistance limits of cortical bone. Von Mises stress was higher on the distal region of distal implants of all-on-four and M-4 techniques. Higher stress concentration was seen on angled abutments of zygomatic implants. The highest values of minimal compression stresses were concentrated on peri implant-bone tissue, especially in the model of All-on-4. Therefore, the present finite element analysis revealed that the four configurations of treatment (six implants axially installed, all-on-four technique, M-4 technique, and four conventional implants with two zygomatic implants) for the totally edentulous maxilla are feasible and safe, from a biomechanical point of view.
**Keywords**: Finite element analysis; Dental implants; Edentulous jaw; Biomechanical phenomena.

**Resumo**
O objetivo deste estudo é avaliar por meio da análise de elementos finitos diferentes técnicas de reabilitação de maxila totalmente edêntula, considerando implantes, tecido ósseo, infraestrutura metálica e características de componentes protéticos, a partir de um modelo tridimensional. A distribuição do estresse no tecido ósseo, implantes e componentes foi analisada com quatro configurações (seis implantes instalados axialmente, técnica all-on-four, técnica M-4 e quatro implantes convencionais com dois implantes zigomáticos). Maior tensão no tecido ósseo foi encontrada em torno de implantes distais, em todos os grupos de tratamento, sem exceder os limites de resistência do osso cortical. O estresse de Von Mises foi maior na região distal de implantes distais das técnicas all-on-four e M-4. Maior

concentração de estresse foi observada em componentes angulares de implantes zigomáticos. Os maiores valores de estresse mínimo de compressão foram concentrados no tecido ósseo peri implantar, especialmente no modelo de All-on-4. Portanto, a presente análise de elementos finitos revelou que as quatro configurações de tratamento (seis implantes instalados axialmente, técnica all-on-four, técnica M-4 e quatro implantes convencionais com dois implantes zigomáticos) para a maxila totalmente edêntula são viáveis e seguras, do ponto de vista biomecânico.
**Palavras-chave:** Análise de elementos finitos; Implantes dentários; Maxila edêntula; Fenômenos biomecânicos.

**Resumen**

El objetivo de este estudio es evaluar, por medio del análisis de elementos finitos, diferentes técnicas de rehabilitación para maxilares superiores totalmente edéntulos, considerando implantes, tejido óseo, infraestructura metálica y características de los componentes protésicos, a partir de un modelo tridimensional. La distribución del estrés en el tejido óseo, implantes y componentes protésicos fue analizada con cuatro configuraciones (seis implantes instalados axialmente, técnica all-on-four, técnica M-4 y cuatro implantes convencionales con dos implantes cigomáticos). Se encontró una mayor tensión en el tejido óseo alrededor de los implantes distales, en todos los grupos de tratamiento, sin exceder los límites de resistencia del hueso cortical. El estrés de Von Mises fue mayor en la región distal de los implantes distales en las técnicas all-on-four y M-4. Se observó una mayor concentración de tensión en los componentes angulados de los implantes cigomáticos. Los mayores valores de tensión mínima de compresión fueron concentrados en el tejido óseo peri implantar, especialmente en el modelo All on Four. Por lo tanto, el presente análisis de elementos finitos reveló que las cuatro configuraciones de tratamiento (seis implantes instalados axialmente, técnica all-on-four, técnica M-4 y cuatro implantes convencionales con dos implantes cigomáticos) para el maxilar superior totalmente edéntulo son factibles y seguras, desde el punto de vista biomecánico.
**Palabras clave:** Análisis de elementos finitos; Implantes dentales; Maxilar edéntulo; Fenómenos biomecánicos.

## 1. Introduction

The rehabilitation of totally edentulous maxilla is challenging for clinicians especially due to bone irreversible atrophy that limits the ideal positioning of implants. Maxillary atrophy, which happens after superior tooth loss, is considered a progressive, chronic, and probably multi-factorial disease that affects millions of edentulous patients around the world (Atwood, 1971; Peñarrocha-Oltra et al., 2013).

Among several approaches, anchorage techniques have been chosen by dentists and patients due to reduced treatment time as well as reduced costs and morbidity (Balshi et al., 1995; Calandriello & Tomatis, 2005; Jensen & Adams, 2009; Maló et al., 2015; Peñarrocha-Oltra et al., 2013; Rodríguez et al., 2016; Stella & Warner, 2000; Weischer et al., 1997).

The use of tilted implants presents some advantages when compared to axially placed implants since they provide greater implant-bone contact, better biomechanical positioning for prostheses (by reducing or eliminating cantilever use), and greater primary stability (Asawa et al., 2015; Calandriello & Tomatis, 2005; Mattsson et al., 1999; Peñarrocha-Oltra et al., 2013; Zampelis et al., 2007) One of the reports in the literature of tilted implants was presented by Mattson et al., in which this surgical technique was introduced as an economic, simple, and viable alternative, compared to more demanding technical resources as bone grafting (Mattsson et al., 1999).

The use of a reduced number of implants on maxillary rehabilitation has been encouraged after successful outcomes in several clinical studies that reported similarities to rehabilitation with 4 or 6 implants (Brånemark et al., 1995; Malo et al., 2003, 2005; Peñarrocha-Oltra et al., 2013). Immediately loaded implants have become a viable treatment modality for fixed-protheses through the association of tilted and axially placed implants (Malo et al., 2003, 2005). Moreover, with technique improvement and the development of more favorable implant designs, atrophic maxilla rehabilitation with 4 tilted implants was possible. Those are placed at up to 30 off-axis, involving the nasal lateral bone and providing high torque for immediate provisional prosthesis installation (Jensen & Adams, 2009, 2014)

The viability of atrophic maxilla rehabilitation with 4 or 6 implants can be proven by finite element analysis, whose results do not exceed the limits of bone tissue, implants, and abutments resistance (Bhering et al., 2016; Bozyel & Faruk, 2021).

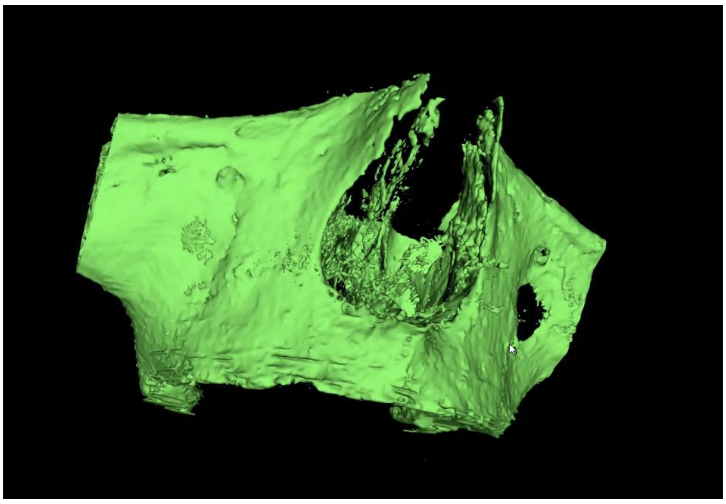
Rehabilitation with intraoral implants fixed in the zygoma was initially described in association to prosthetic obturator with partial resection to provide stability and oronasal separation (Weischer et al., 1997). Thus, its indication was extended to the severely atrophic maxilla, and it was consolidated as an alternative treatment to great reconstructions, with the possibility of immediate loading with high success rates and predictability (Brånemark et al., 2004; Stella & Warner, 2000).

The aim of this study is to evaluate by finite element analysis different techniques of totally edentulous maxilla rehabilitation, considering implants, bone tissue, metallic infra-structure, and prosthetic abutments characteristics.

## 2. Methodology

The model used in this study was constructed on Invesalius software (CTI Renato Archer, Campinas, Brazil) based on CT data obtained from a patient with a totally edentulous maxilla of Ilapeo College. Three-dimensional models grouped on CAD software (Autodesk Inventor Professional, San Rafael, USA) and then transferred to the FEMAP software (FEMAP with NX Nastran, v11.3.2 64-bits, Siemens, Texas, USA) for finite element analysis (Figure 1).

**Figure 1** Three-dimensional model created on Invesalius software.



Source: Authors (2022).

The distal cantilever length in all treatment models were 12mm (Watson et al., 1991). For the analysis, materials were considered as follows: bone type II, titanium grade 4 (osseointegrated implants), and titanium grade 5 (prosthetic bar, abutments, and screws). All materials were considered isotropic, homogenous, and linearly elastic. The modulus of elasticity is defined as the relationship between the stress and strain of the material, indicating its stiffness. Poisson coefficient refers to the absolute value of the relationship of the load effect between transverse and longitudinal deformation on an axial traction axis (Table 1).

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**Table 1.** Properties of the materials included in finite element analysis.

| Materials properties | | | | |
|---|---|---|---|---|
| **Material** | **Elastic modulus (MPa) - Stiffness** | **Elastic limit (MPa)** | **Poisson´s ratio (μ)** | **References** |
| **Bone type II** | 5500 | 170 Compression<br>100 Tension | 0,3 | Tada et al.(Tada et al., 2003),<br>Almeida et al.(Almeida et al., 2010),<br>Bozkaya et al.(Bozkaya et al., 2004) |
| **Titanium grade 4** | 103000 | 703 | 0,361 | ASTM F 67 |
| **TI6AL4V-ELI (Titanium alloy)** | 105000 | 881 | 0,361 | ASTM F 136 |

| Interface | | | |
|---|---|---|---|
| **Materials** | **Nature of interface** | **Coefficient of friction** | **References** |
| **Bone x implant** | Bonded | - | Eskitascioglu et al.(Eskitascioglu et al., 2004) |
| **Implant x abutment x prosthetic screw x prosthetic bar** | Friction | 0,2 | Haack et al.(Haack et al., 1995)<br>Lang et al.(Lang et al., 2003) |

Fonte: Dados da pesquisa (2022).

Treatment groups were divided into 4 (Figure 2), as described below:

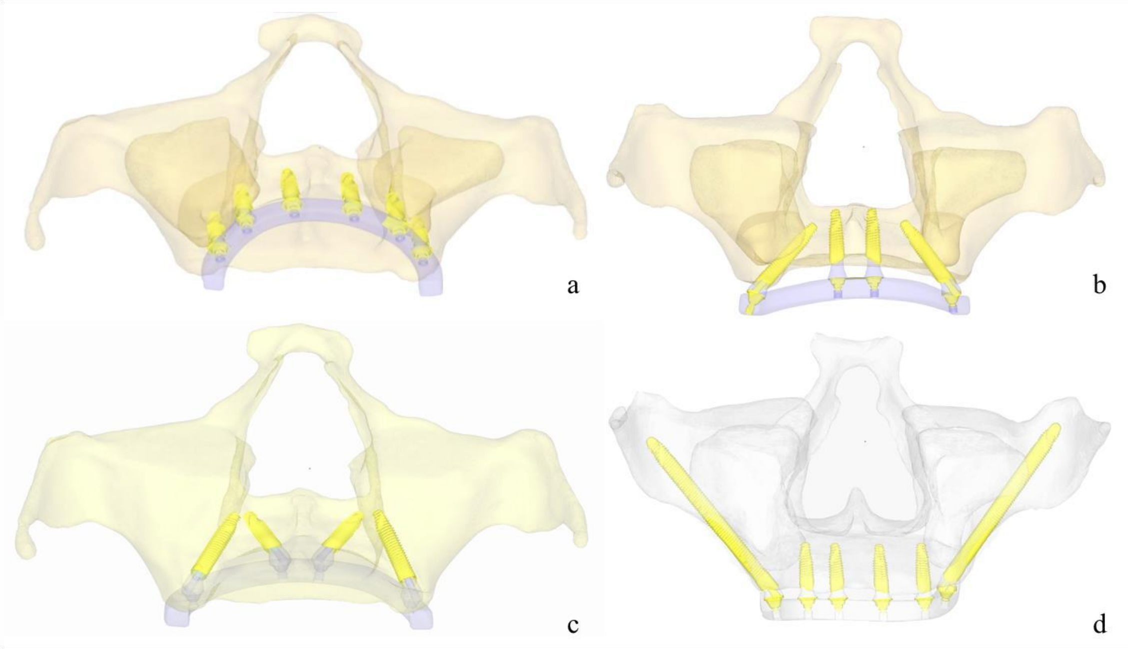
G1: Six Helix GM implants (GrandMorse, Neodent, Curitiba, Brazil) axially installed with 3.75mm of diameter and 11.5mm of length, and straight mini conical abutment with 2.5mm of gingival height.

G2: Four Helix GM implants (GrandMorse, Neodent, Curitiba, Brazil), being two of them (3.75x11.5mm) installed in the anterior region and the other two implants (3.75x18mm) installed tilted in the posterior region of the jaw, with 30 degrees mini conical abutments with 3.5 mm of gingival height. This technique is known as All-on-Four.

G3: Four Helix GM implants (GrandMorse, Neodent, Curitiba, Brazil), being two of them (3.75x13mm) tilted installed in the anterior region of the jaw (in direction to the canines) with 30 degrees mini conical abutments with 3.5mm of gingival height. The other two implants (3.75x18mm) were tilted installed in the posterior region with 30 degrees mini conical abutment with 3.5mm of gingival height. This is known as M-4 technique.

G4: Two GM Zygomatic implants (GrandMorse, Neodent. Curitiba, Brazil) installed using the technique introduced by Stella and Werner (4) with 45 mm of length and two 45 degrees mini conical abutments (2.5mm of gingival height). In the anterior maxilla region, four 3.5x10mm Helix GM implants (GrandMorse, Neodent. Curitiba, Brazil) were installed with mini conical abutments with 2.5mm of gingival height.

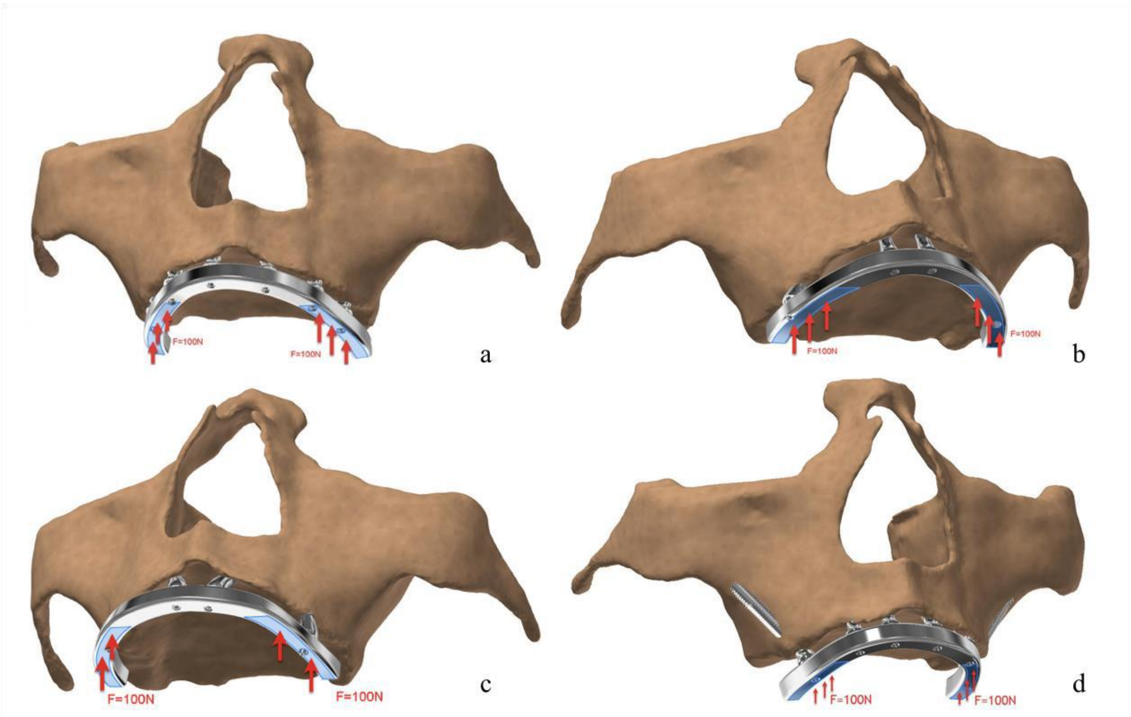
**Figure 2** Three-dimensional models of treatment alternatives for the totally edentulous maxilla. G1: 6 axially placed implants (a). G2: All-on-four technique (b). G3: M-4 technique (c). G4: Two zygomatic and four conventional implants (d).




Source: Authors (2022).

In all models simulated in the finite element analysis, the load applied was 100N, perpendicular to the metal bar, on each side, totaling 200N, representing the occlusal forces in the posterior region (Figure 3).

**Figure 3** Occlusal forces on posterior region of each group. The total occlusal loading applied on each side was 100N.

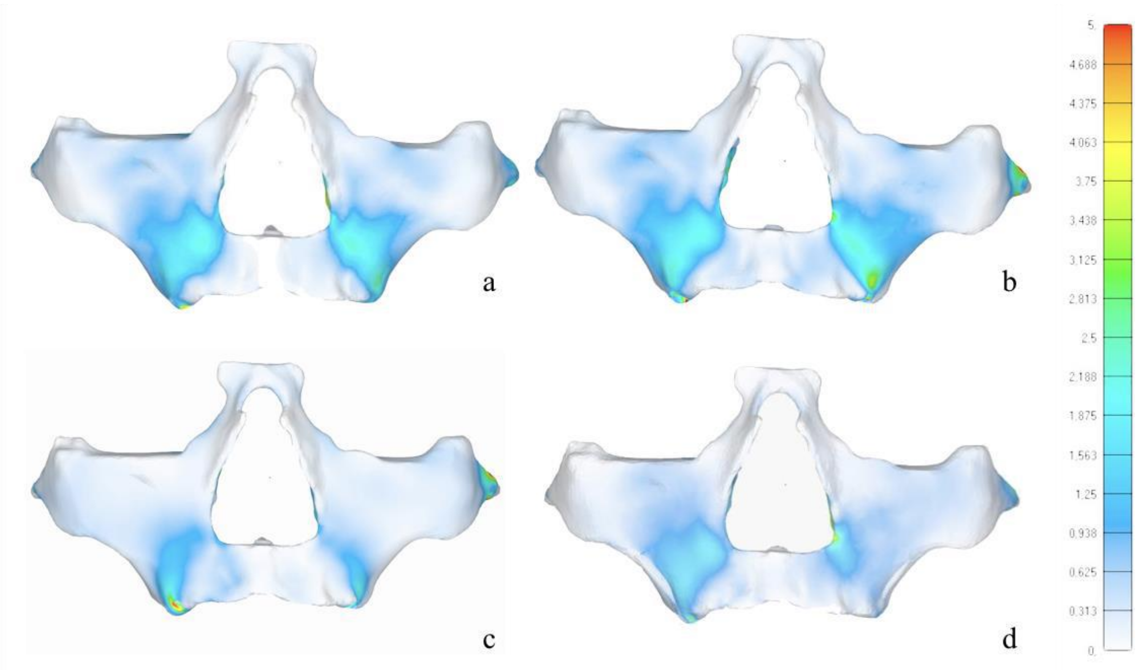



Source: Authors (2022).

## 3. Results

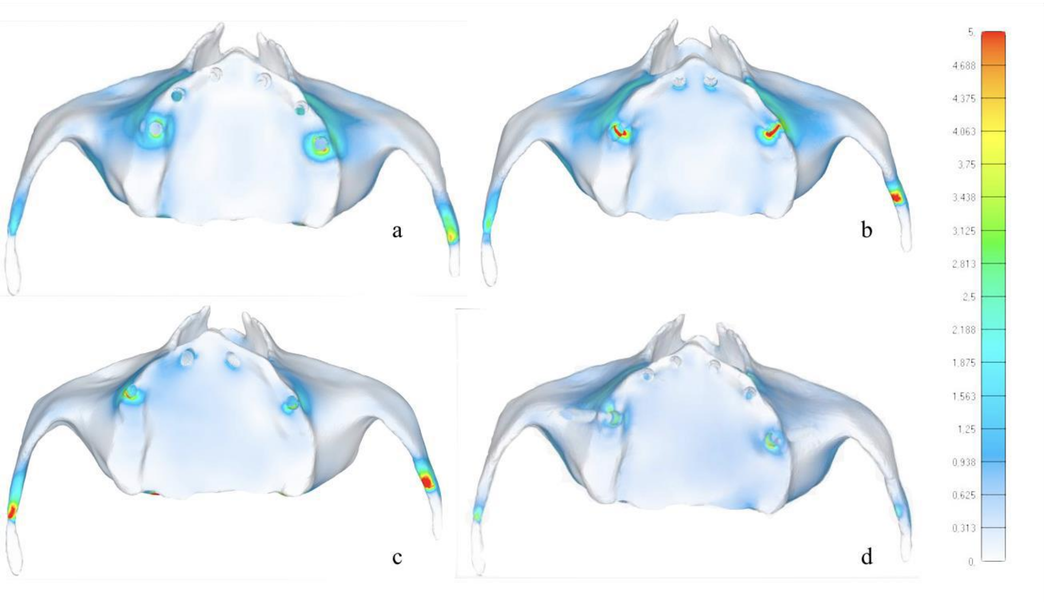
The present finite element analysis showed that greater tension on bone tissue (represented in colors which intensity follows a scale on the right side of each model) was found especially around distal implants, in all treatment groups, but not exceeding 5Mpa neither resistance limits of cortical bone (170MPa compression and 100MPa tension) (Figures 4 and 5).

**Figure 4** Frontal view of stress distribution on bone tissue in G1 (a), G2 (b), G3 (c) and G4 (d).




Source: Authors (2022).

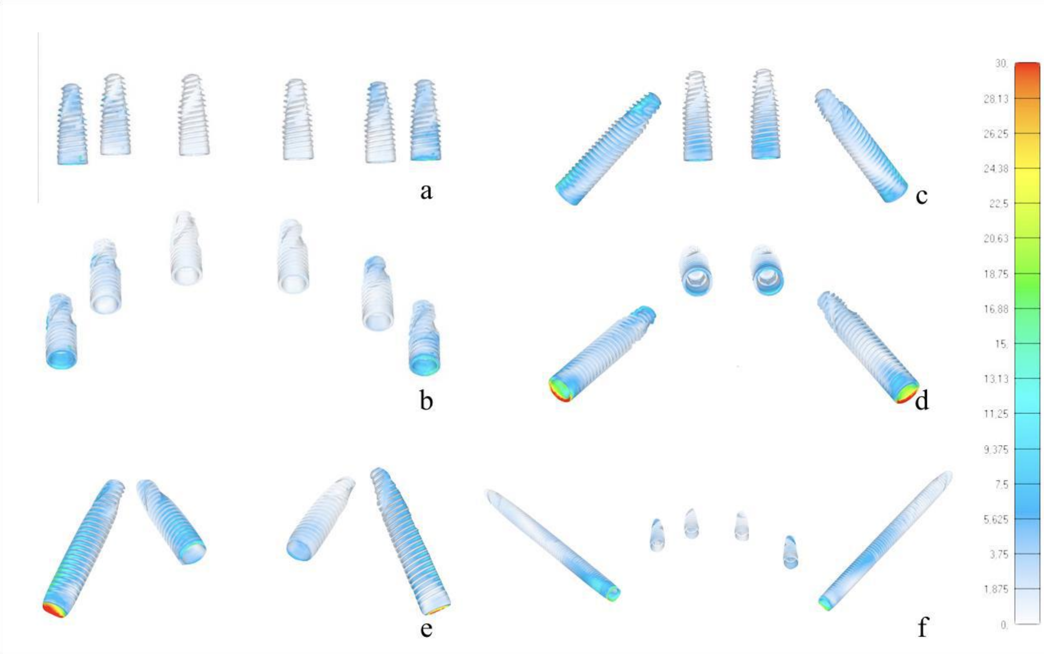
**Figure 5** Occlusal view of stress distribution on bone tissue in G1 (a), G2 (b), G3 (c) and G4 (d).




Source: Authors (2022).

The Von Misses stresses on implants were concentrated on the distal regions of distal implants, reaching maximum values of 30MPa, on groups 2 and 3 techniques. Those are considered as very low values, under the titanium alloy grade IV elastic limit (703 MPa) (Figure 6).

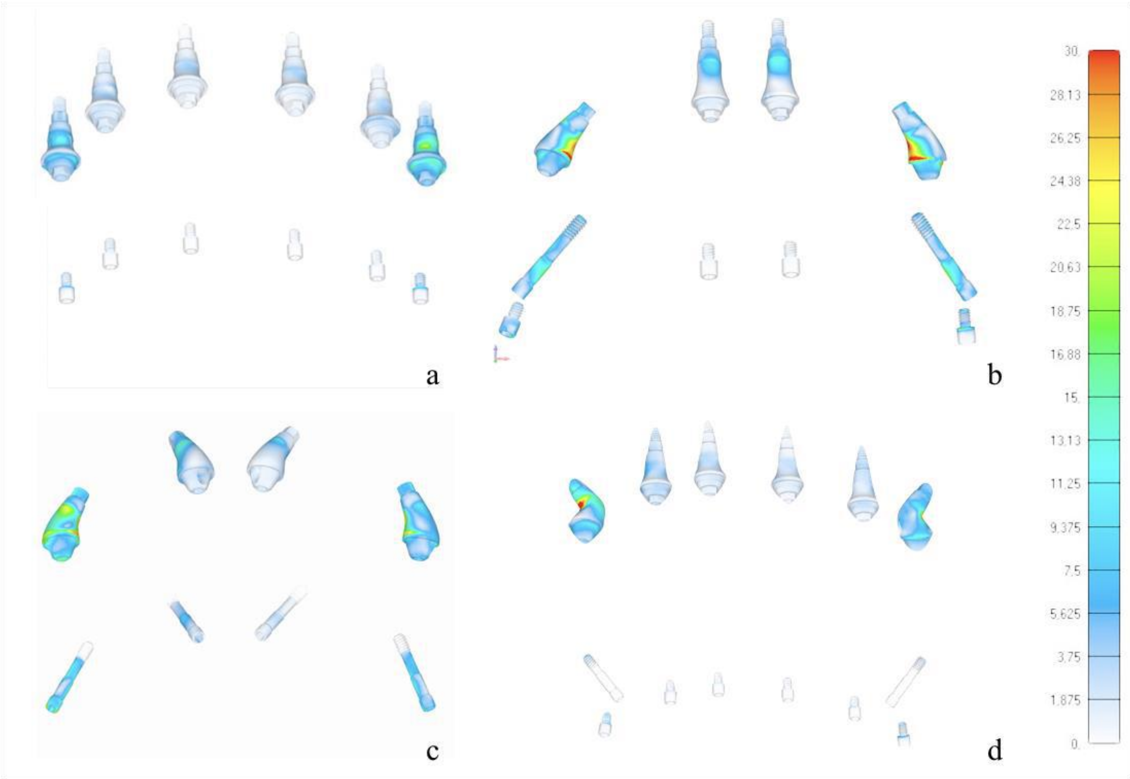
**Figure 6** Von Misses stress distribution on implants used in the four treatment groups. Group 1 (a, b), group 2 (c,d), group 3 (e) and group 4 (f).




Source: Authors (2022).

The distribution of stresses on mini conical abutments showed that higher stress values were concentrated on the mesial surface of angled abutments of groups 2, 3, and 4. Furthermore, higher stress concentrations were seen in the group of zygomatic implants treatment in which 45 degrees mini conical abutments were used. Maximum values of stress don´t exceed 30MPa in all groups, and those values are well below the titanium alloy grade 5 elastic limit of 881MPa (Figure 7). Stresses on screws of mini conical abutments in all-on-4 technique (group 2) were concentrated on screw body. In the M-4 technique (group 3), there were no stresses on screw threads, suggesting that in this treatment configuration the produced stress will not lead to its loosening. Maximum stress values on screw body did not exceed 20MPa and on prosthetic screw 5MPa, being those well below titanium grade 5 elastic limit (881MPa) (Figure 7).

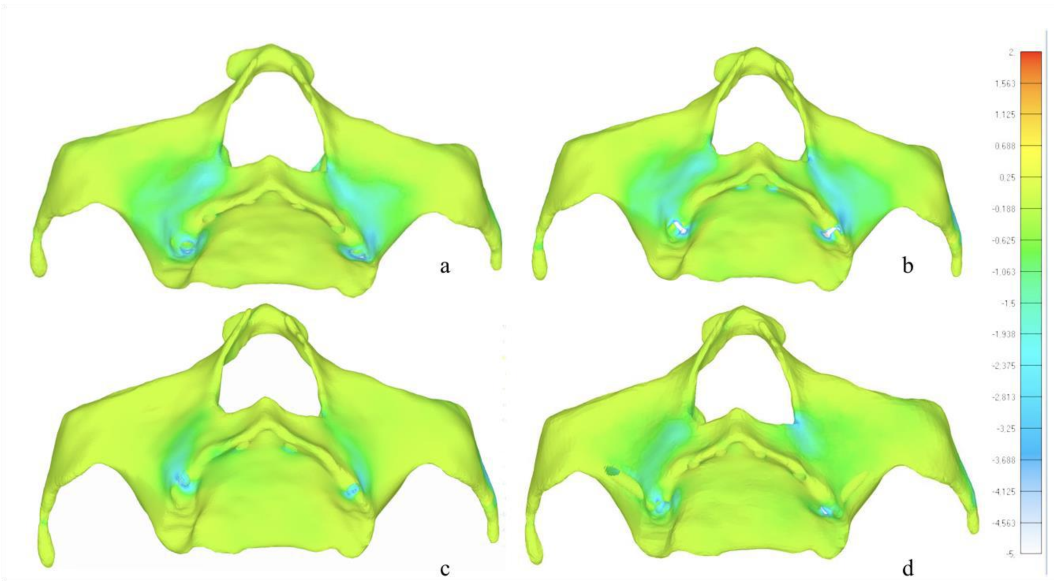
**Figure 7** Von Mises stresses distribution on mini conical abutments and prosthetic screws of groups1 (a), group 2 (b), group 3 (c) and group 4 (d).




Source: Authors (2022).

The highest values of minimal compression stresses were concentrated on peri implant-bone tissue, especially in the model of conventional All-on-4 treatment, and it didn´t exceed 5MPa, which is well below of cortical bone resistance limit (170MPa) (Figure 8).

**Figure 8** Distribution of minimal compression stress in the four groups: G1 (a), G2 (b), G3 (c) and G4 (d).




Source: Authors (2022).

## 4. Discussion

The finite element analysis method was first introduced by (Selna et al., 1975), and has been exhaustively used in implantology to investigate and preview patterns of stress distribution on the bone-implant interface, in several clinic scenarios of prosthetic loading, designs, and implant distribution. Through this analysis, it is possible to resolve many complex structural issues by dividing and relating them into simple geometric shapes using mathematical techniques (Almeida et al., 2015; Bhering et al., 2016; Bozkaya et al., 2004; Bozyel & Faruk, 2021; Choi et al., 2014; Haack et al., 1995; Selna et al., 1975). In the present study, we investigated bone tissue, implants, and prosthetic abutments behavior concerning the generated stress in four treatments for totally edentulous maxilla rehabilitation.

Atrophic maxilla rehabilitation by means of implant-supported prostheses can be made in conjunction with reconstruction techniques, such as the use of block or particulate grafts, associated or not to guided bone regeneration with meshes or morphogenic proteins (Rh-BMP). Another option is anchorage techniques, based on tilted and/or long implants that provide greater bone-implant contact and reach to regions of greater bone density, increasing primary stability of implants, enabling faster rehabilitation, with lower cost and lower patient morbidity (Peñarrocha-Oltra et al., 2013).

The 6 implants rehabilitation (G1), reported by several authors (Bhering et al., 2016; Brånemark et al., 1995; Brunski, 2014; Silva et al., 2010) was compared in this study to two other rehabilitation techniques with 4 implants: conventional All-on-four® (G2) and M-4 (G3). As reported by Bhering et al. (Bhering et al., 2016) and Branemark et al. (Brånemark et al., 1995), we observed that although 6 implant rehabilitation presented more favorable biomechanical distribution when compared to 4 implants rehabilitation, the results were well below the resistance limits of bone and materials involved in the rehabilitation (titanium grade 4 – implants; titanium grade 5 – prosthetic abutments).

It has been suggested (Jensen & Adams, 2014) that implants disposition in the shape of "M", as in G3, has a favorable biomechanical configuration, which allows immediate loading, even when primary stability is not achieved in all implants. It has been considered that this disposition provides the required conditions to promote osseointegration only through secondary stability promoted by biomechanical immobilization and slurry (Jensen & Adams, 2014). Moreover, through the results of this finite element analysis, we found that G3 has better biomechanical distribution than G2 (conventional All-on-four®), in which areas with Von Mises stress peaks of 30MPa were more extensive.

Rehabilitation with zygomatic implants is well documented in the literature, presenting great success rates and low complication rates (Aparicio et al., 2014; Chrcanovic et al., 2016; Vrielinck et al., 2022; Yates et al., 2014). In the present study, atrophic maxilla rehabilitation with 2 zygomatic implants with 45 degrees mini conical abutments, installed according to Stella and Werner technique (2010) associated with 4 anterior conventional implants was evaluated in G4. Von Mises stresses concentrated on 45 degrees mini conical abutments were greater than on straight or 30 degrees mini conical abutments (G2 and G3), reaching peaks of 30MPa, but not exceeding titanium grade 5 elastic limits (881 MPa).

## 5. Conclusion

The present finite element analysis revealed that the four treatment options for totally edentulous maxilla are feasible and safe, from a biomechanical point of view. All stress peaks, in all rehabilitation components (bone tissue, implants, prosthetic abutments, and prosthetic screws) were well below the limits and resistance of each material.

Since finite element analysis is a computational study model that simulates clinical scenarios with fully controlled variables, we suggest that the findings of this study should be further investigated by conducting clinical studies.

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