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Original Article

Comparison of Biomechanical Effects of All-on-Four Implant Prostheses with Different Types and Weights: A Three-Dimensional Finite Element Analysis

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ABSTRACT

Objective: The aim of this study is to comparatively evaluate the stress values created by all-on-four prostheses of different types and weights on the implant, infrastructure, and peri-implant bone tissue under occlusal forces using the three-dimensional (3D) finite element analysis (FEA) method.

Methods: A completely edentulous lower jaw model was designed in a computer environment using the FEA method, and implants were placed according to the all-on-four technique. Five different infrastructure materials were simulated in the 3D models, including chromium-cobalt (Cr-Co), titanium, zirconia, fiber, and polyetheretherketone (PEEK). The superstructure material of the prostheses was designed as monolithic zirconia crown and composite resin gingiva, which would be the same in all models. The weights of the created all-on-four prosthesis models were calculated. A rigid food material was used for a 100 newton (N) force application. Maximum principal (Pmax) and minimum principal (Pmin) stress values for cortical bone and Von mises stress values for the implant and infrastructure were calculated.

Results: The weight of prostheses with different types of infrastructures affected the stress distribution in the implant, infrastructure, and peri-implant bone tissue. Lower stress values were observed in the implants and peri-implant bone tissues in Cr-Co, titanium, and zirconia infrastructures compared to fiber and PEEK. When the stresses occurring within the infrastructure materials were evaluated, lower stresses were obtained in fiber and PEEK infrastructures.

Conclusion: Following the results of the biomechanical comparison made with 3D FEA, it can be said that long-term success can be achieved in the implant and the bone tissue around the implant as the elasticity modulus of the infrastructure material increases and the use of Cr-Co, titanium, and zirconia materials as infrastructures can be more advantageous. The weight of the modeled all-on-four prostheses did not reach harmful stress values in the bones around the implant together with the occlusal forces.

Keywords: Dental implant, finite element analysis, biomechanics, bone tissue

INTRODUCTION

Advances in science and technology have led to the development of new solutions to the existing disadvantages of traditional prostheses. Recent advancements in dental implant technology, in combination with the all-on-four treatment approach, have typically led to shorter treatment durations and reduced risks, including morbidity, for patients with complete tooth loss. This method was initially developed to address intricate prosthetic and surgical challenges associated with anatomical constraints and has since gained widespread adoption and increasing utilization.[1]

Many studies evaluating prosthesis materials have reported that lightweight restorative materials are more advantageous.[2,3] A previous study suggested that reinforced composite infrastructures could be a suitable alternative to traditional metal infrastructures used in implant-supported prostheses. The authors also identified a lighter

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infrastructure as an advantage in terms of prosthetic treatment. However, it is still unknown whether the weight of the prosthesis has an effect on the bone tissues around the implants. The materials used as infrastructure materials in implant-supported prostheses affect the stress distribution transmitted to the bone, implant, prosthesis structures, and support components during function, and therefore the selection of infrastructure is very important for achieving clinical success. Full arch implant-supported dentures are one of the most comprehensive restoration options in dentistry. The majority of the structure of these prosthetics may be made of metal and ceramic, resulting in a higher volume and density of material.[4]

It has been reported that a lighter material provides advantages in obturator prostheses for patients with maxillary defects; however, information on the influences of prosthesis weight for implant-supported prostheses remains scarce.[5] Some researchers have suggested that prostheses with a chromium-cobalt (Cr-Co) infrastructure are more suitable than those with a titanium infrastructure in terms of the stresses applied to the bone surrounding the implant.[6] Despite this, the Cr-Co infrastructure contradicts the lighter designs recommended by the authors, as it can be heavier than the titanium alternative. Currently, there is no study in the literature comparing the biomechanical effects of different prosthesis weights designed according to the all-on-four concept on mandibular bone.

Excessive bone stress around osseointegrated implants may lead to unfavorable bone remodeling and potential loss of osseointegration.[7] Thus, every decision made during surgical and prosthetic planning must be carefully considered to optimize the biomechanical response to occlusal forces.[8] What remains unclear in the literature is whether prosthesis weight will benefit or harm the bone tissue surrounding the implants. Mechanical stress can have both positive and negative impacts on alveolar bone remodeling. According to Wolff's law, bone tissue may adapt and maintain its structure depending on the level of stress applied.[7]

MAIN POINTS

- For all groups, maximum stresses in the cortical and trabecular bone were observed in the posterior implant socket and did not exceed the fracture strength of the bone.
- As the elasticity modulus of the material used in the infrastructure increases, the stresses transmitted to the bone and the implant decrease.
- It is thought that PEEK and fiber materials are risky for long-term success in prosthetic restorations to be made according to the all-on-four treatment concept, and Cr-Co, zirconia, and titanium materials are more suitable.
- Rigid infrastructure materials (Cr-Co, titanium, zirconia) with low-stress transmission properties can be preferred in the posterior region of the mandible where resorption is high.

During mastication, the forces acting on artificial teeth are compressive, generated by the contact of the occlusal surfaces with the food bolus.[9] In the lower jaw, this occlusal force may align with the gravitational pull of the denture, potentially increasing the stress on the bone around the implants.

Therefore, the hypothesis of our study is that all-on-four prostheses with different weights made of different types of infrastructure materials will not affect stress distributions on the implant, infrastructure and peri-implant bones under occlusal forces.

MATERIAL AND METHODS

A three-dimensional (3D) model of the edentulous mandible was developed using data from the Visible Human Projects (US National Library of Medicine, Bethesda, MD, USA). This model was adjusted to exhibit class 2 atrophy in the interforaminal regions based on the Luhr classification.[10] These alterations were made using VRMESH (VirtualGrid Inc, Bellevue City, WA, USA) and Rhinoceros 4.0 (Robert McNeel & Associates, Seattle, WA, USA) software programs. The implants and prosthetic components were digitized using an optical scanner (Smart Optics 3D scanner, Bochum, Germany) with a 10 μm precision, and the data were reconstructed with Rhinoceros 4.0 and VRMESH software for structural modeling.

In the lateral region of the mandible, right-angled implants measuring 4.1 mm in diameter and 10 mm in length (Bone Level, Straumann, Basel, Switzerland) were modeled. In the second premolar region, angled implants with a diameter of 4.1 mm, a length of 12 mm, and a 30-degree tilt (Bone Level, Straumann, Basel, Switzerland) were modeled. Straight multi-unit abutments (Bones Level, Straumann, Basel, Switzerland) were utilized for the anterior implants, while angled multi-unit abutments (Bone Level, Straumann, Basel, Switzerland) were used for the posterior implants.

Five main models were created in the lower jaw according to the type of infrastructure to be used on the implants. These models were created from Cr-Co, titanium, zirconia, polyetheretherketone (PEEK), and fiber infrastructure materials (Figure 1). The superstructure materials were designed as monolithic zirconia crown and composite resin gingiva, which will be the same in all models. The materials used in this study were assumed to be homogeneous,

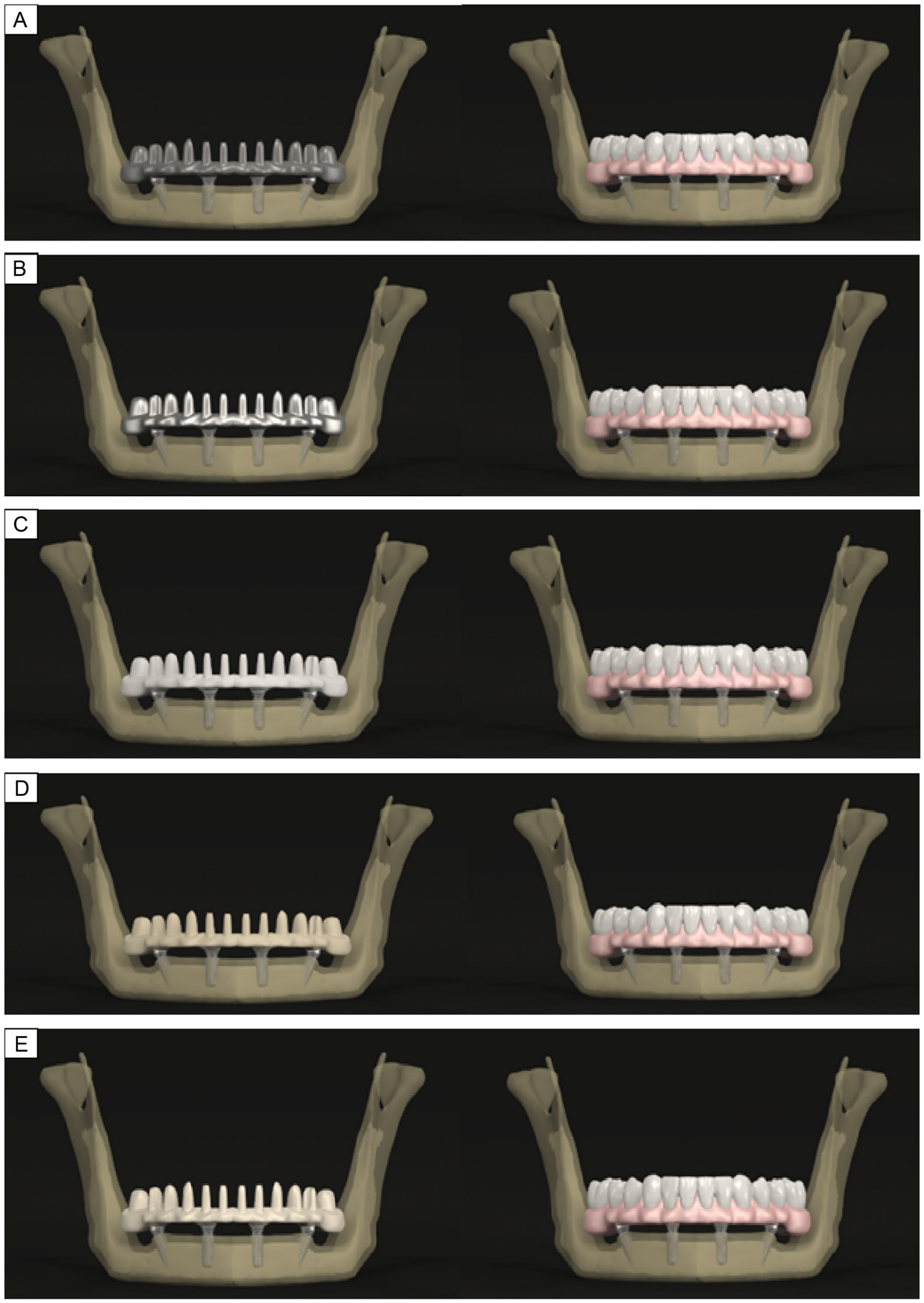

Figure 1. Models used in the study: (A) chromium-cobalt; (B) titanium; (C) zirconia; (D) polyetheretherketone; and (E) fiber.

linear elastics, and isotropic. The mechanical properties of the materials used in the study are shown in Table 1.[9,11]

In this study, gravitational force is defined as an acceleration of 9.8065 m/s^2 along the negative Z axis of the coordinate system. Simulations were conducted for 5 different primary models, each based on varying prosthesis materials. The weights (P) of each prosthesis were determined using the equation $P = m \times g$, where g represents the gravitational acceleration and m is the mass of the object at a specific spatial point. To calculate the mass, the formula $m = v \times \mu$ was applied, with v being the volume in cm^3 and μ the density in g/cm^3. The material densities were sourced from existing literature, while the volumes were obtained using 3D modeling software. Once the mass of each material was determined, the corresponding prosthesis weight was calculated (Table 2).

For each model, an occlusal force was delivered to the left first molar region using spherical solids simulating the food material. The occlusal force was applied to the center point of a rigid foodstuff with a radius of 1 cm and was loaded perpendicularly to 100 N. The loading was planned to simulate the chewing force. When evaluating the finite

Table 1. Mechanical Properties of the Materials

Materials	Young Modulus (Mpa)	Poisson's Ratio	Density (g/cm^3)
Cortical bone	13.700	0.30	
Spongiosa bone	1.370	0.30	
Titanium (implant, screw, and abutment)	110.000	0.35	
Titanium infrastructure	110.000	0.28	4.50
Zirconia infrastructure	205.000	0.22	5.68
Chromium-cobalt infrastructure	218.000	0.33	8.00
PEEK infrastructure	4.000	0.36	1.32
Fiber infrastructure	18.800	0.22	1.68
Monolithic zirconia	210.000	0.29	6.08
Composite	11.000	0.28	2.4
Food stuff (AISI 1005 Steel)	200.000	0.29	

PEEK, polyetheretherketone; AISI, American Iron and Steel Institute.

element stress analysis results, the implant in the left posterior region was numbered 1, the left anterior implant 2, the right anterior implant 3, and the right posterior implant 4. To prevent displacement, the model was fixed to the lower part of the jawbone so that it would not move at all in any range of freedom. It is assumed that there is complete osseointegration between the implant and the bone surfaces. All bodies are assumed to be perfectly connected to each other via their contact surfaces, without any relative movement along their entire interface. The maximum (Pmax) and minimum (Pmin) principal stress values for the cortical bone were computed. The infrastructure and implants, being classified as ductile materials, were analyzed using the Von Mises stress criteria.

RESULTS

Stresses in the Cortical Bone Around the Implant

Maximum Principal Stresses

While the highest compressive stress values in the cortical bone in all models were seen around implant number 1 (1>2>4>3), the stress values at the selected nodal points were as follows from high to low: PEEK (−9.854796 MPa) > fiber (−9.549290 MPa) > titanium (−8.928370 MPa) > zirconia (−8.670070 MPa) > Cr-Co (−8.646618 MPa) (Figure 2).

Minimum Principal Stresses

While the highest tensile stress values in the cortical bone were seen around implant number 2 in all models (2 > 1 > 3 > 4), the stress values at the selected nodal points in the models were as follows from high to low: PEEK (6.845911 MPa) > fiber (6.180720 MPa) > titanium (4.881706 MPa) > zirconia (4.468925 MPa) > Cr-Co (4.421059 MPa) (Figure 3).

Stresses in Implants

When the stresses around the implant were examined, the highest values were seen at the selected node points in region 1 closest to the force-applied area in all models (1 > 2 > 3 > 4). The stress values were as follows from high to low: fiber (97.001716 MPa) > polyetheretherketone (92.911129 MPa) > titanium (89.673009 MPa) > zirconia (85.144571 MPa) > Cr-Co (84.809044 MPa) (Figure 4).

Stresses in Infrastructure

When the stresses around the infrastructure were examined, the highest values were seen at the selected node points in region number 1 closest to the force applied region in all models (1 > 2 > 3 > 4). The stress values were as follows from high to low: zirconia (34.584074 MPa) > Cr-Co (32.808473 MPa) > titanium (30.802551 MPa) > fiber (22.086659 MPa) > PEEK (10.923247 MPa) (Figure 5).

DISCUSSION

This study evaluated the stress values of the weights of different types of infrastructure materials to be used on implants placed according to the all-on-four treatment concepts in edentulous and resorbed mandibles and the occlusal forces on the implant, infrastructure, and peri-implant bone. The results show that the weights of different infrastructure materials and occlusal forces affect

Table 2. Weight Forces and Weight of Prostheses

	Weight Forces of Prostheses (Newton)	Weight of Prostheses (g)	Infrastructure Volume (cm^3)	Superstructure Volume (cm^3)	
				Gingiva Volume	Crown Volume
Chromium-cobalt	0.550	55.6	3.837	1.977	3.319
Zirconia	0.462	46.7	3.837	1.977	3.319
Titanium	0.417	42.1	3.837	1.977	3.319
Fiber	0.310	31.3	3.837	1.977	3.319
PEEK	0.296	29.9	3.837	1.977	3.319

PEEK, polyetheretherketone.

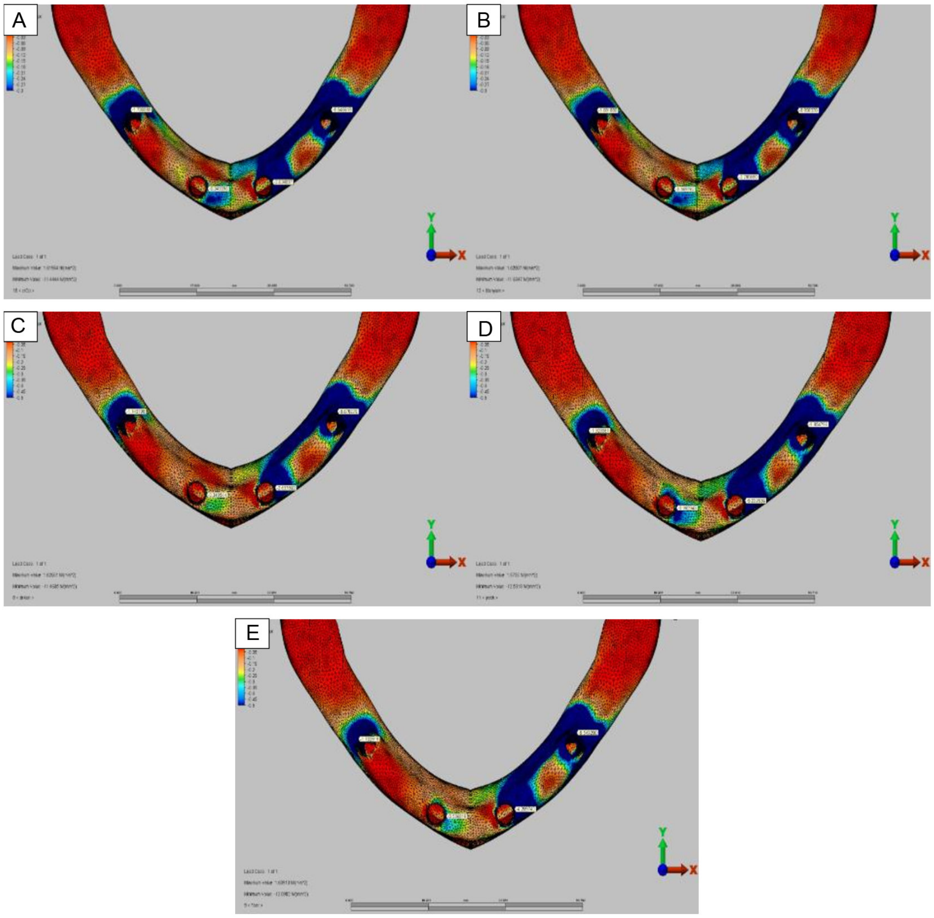

Figure 2. Maximum principal stresses (N/mm^2) on cortical bone: (A) chromium-cobalt; (B) titanium; (C) zirconia; (D) polyetheretherketone; and (E) fiber.

the stress values on the implant, infrastructure, and peri-implant bone. Therefore, our hypothesis is rejected.

Many studies report that lightweight restorative materials are more advantageous;[3] however, the criteria used to differentiate between lightweight and heavy materials have not been clearly defined. In a previous study, lighter prostheses were found to reduce stress on the supporting tissues as a function of the material's weight. However, few studies have explored the impact of prosthesis weight in medical contexts,[12] and even fewer have examined its biomechanical effects on supporting tissues in dentistry.

In prosthetic rehabilitation, there is a general concern that prostheses should be sufficiently heavy to maintain functionality.[13] Research into lighter materials and designs could aid in creating prostheses that better replicate missing body parts. However, this concern may differ when dealing with intraoral prostheses. In a finite elements analysis conducted by Tribst et al.,[14] the effects of prosthesis weight on microstrain in the peri-implant bone were assessed without accounting for occlusal forces. The study modeled a full-arch implant-supported prosthesis with varying numbers of implants (4, 6, or 8) and prosthesis weights (10, 15, 20, 40, or 60 g). The results indicated that heavier prostheses, under the influence of gravity, produced greater strain around the implants. In the modeled prostheses, the highest strain in the peri-implant bone tissue was seen in the models with Cr-Co infrastructure ceramic superstructure, and the lowest strain was seen in the model with PEEK infrastructure acrylic superstructure. In the modeled prostheses, no harmful values were observed for bone strain around the implant. Unlike this study, the current study simulated all-on-four prosthesis rehabilitation in which prosthesis weight and occlusal forces were applied together, and the resulting stresses were found to be in the range of 1-20 MPa. As a result, it was assumed that the alveolar bone was within the range of values suitable for remodeling, and the stress value that could damage the bone tissue was not calculated. Based on these results, dentists and technicians can select the designs and materials that are more advantageous in terms of distributing the chewing load, rather than considering only light or heavy materials.

In the simulated all-on-four prostheses, the superstructure was designed as monolithic zirconia crown

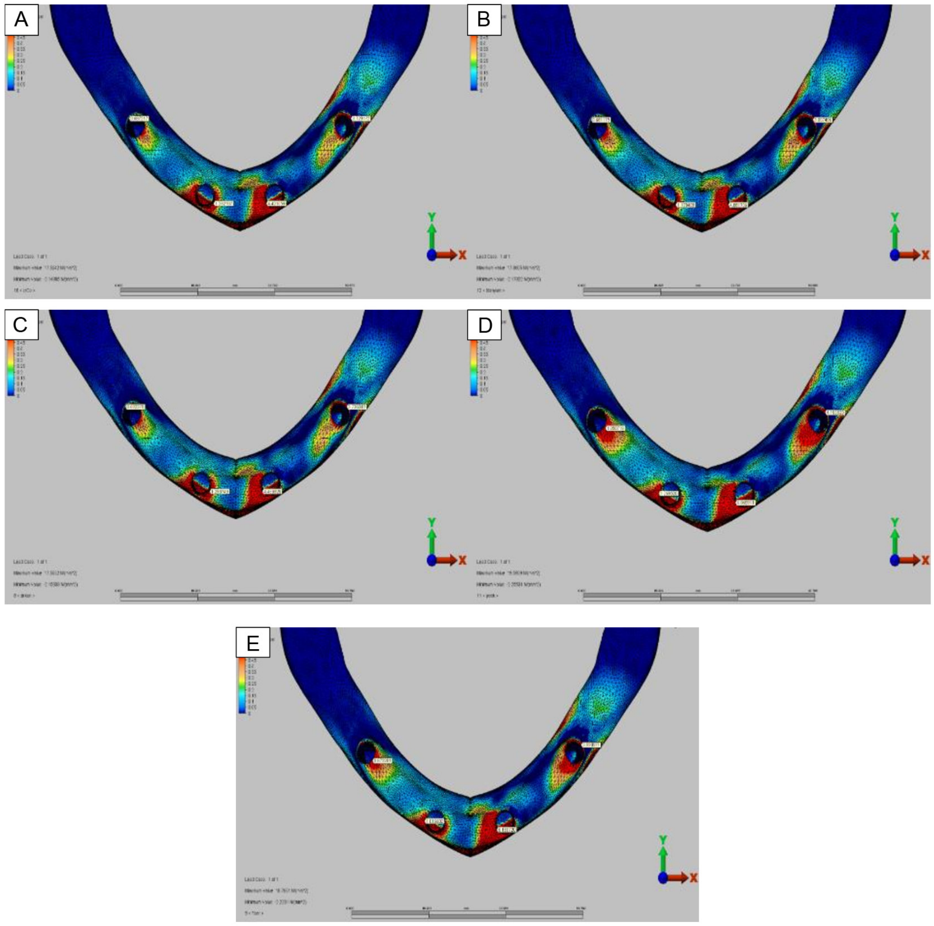

Figure 3. Minimum principal stresses (N/mm²) on cortical bone: (A) chromium-cobalt; (B) titanium; (C) zirconia; (D) polyetheretherketone; and (E) fiber.

and pink composite gingiva in all models. The design with the lightest prosthesis weight in the study was the model with PEEK infrastructure, and this design weights 29.9 g. Although it is the lightest design, it created the highest stress values in the bones with occlusal forces. However, there are no long-term studies demonstrating the success of this prosthetic rehabilitation method. The second lightest prosthesis was the fiber infrastructure model with 31.3 g. This rehabilitation method, although light in weight, created the second highest stress value in the bone with occlusal forces. The third lightest prosthesis designed was a titanium-based model with a weight of 42.1 g. This restorative method has proven its clinical success for approximately 5 years.[15] However, since titanium has a greater affinity for oxygen than traditional casting alloys, this treatment method is not widely used due to the difficulty of casting titanium alloys.[16] Using a titanium infrastructure with a milling technique can solve these difficulties by optimizing use of this metal,[17] which offers lower bone stress values. Another option instead of titanium is to use a Zirconia infrastructure. There are reports of the success of prostheses with zirconia infrastructure for more than 3 years.[18] The use of zirconia materials is due to the high resistance of the material, which eliminates the application of an opaque material layer to the infrastructure due to its white color and high wear resistance.[19] Among the prostheses simulated in this study, it was the second heaviest design with a weight of 46.7 g and created the second least stress values in the bones around the implant together with the occlusal forces. It may cause wear on metal structures that come into contact with the zirconia surface.[20] There are also studies that describe zirconia infrastructures as having a similar biomechanical responses to titanium infrastructures,[21] while other studies describe harder materials causing less damage to bone tissue.[22] These studies generally compared implant-supported prosthesis infrastructures and used the mechanical properties of the material such as elastic modulus and Poisson coefficient.[21,22] The weight of the prostheses is not included.

Chromium-cobalt alloys are widely used in dentistry due to their ease of casting, low cost, and high durability. However, these alloys present difficulties in finishing and polishing due to their high density.[23] Bhering et al.[6] evaluated the stress distribution around implants of

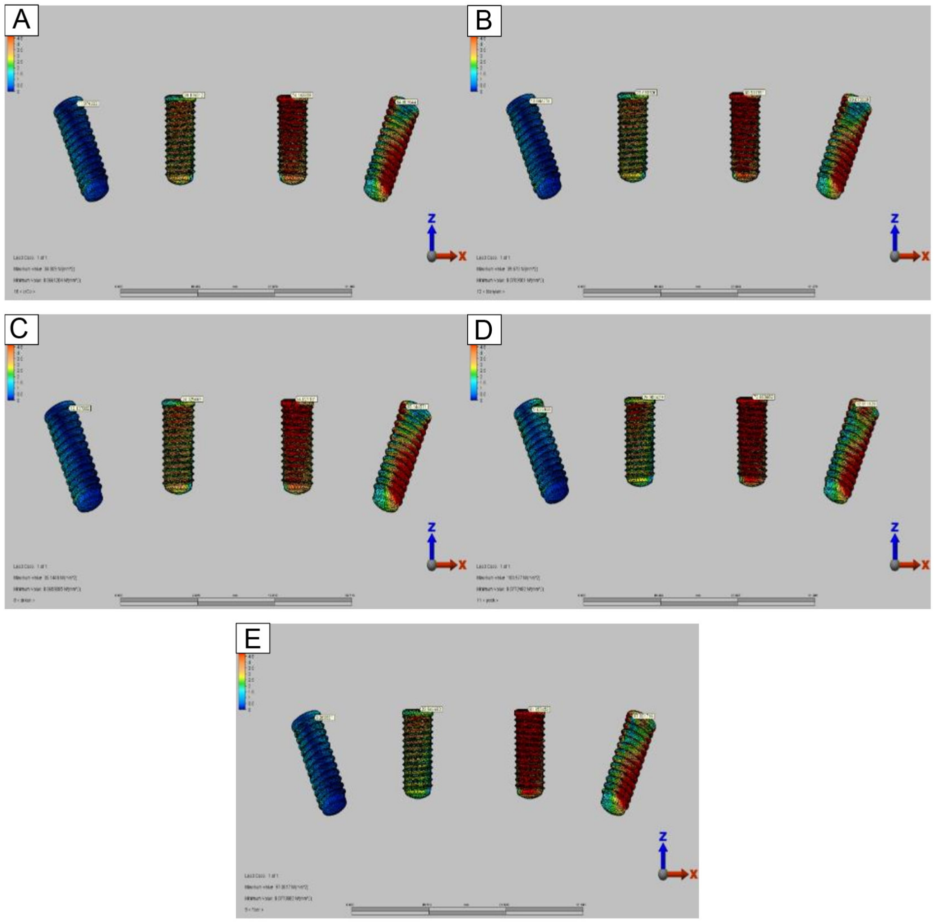

Figure 4. Von mises stresses on implants: (A) chromium-cobalt; (B) titanium; (C) zirconia; (D) polyetheretherketone; and (E) fiber.

different infrastructure materials under occlusal forces. It has been suggested that Cr-Co infrastructure materials have more advantages compared to titanium infrastructures by reducing the tension in the tissues around the implant. In this study, the stresses caused by occlusal forces were similarly investigated by including the weight of the prosthesis. Chromium-cobalt, titanium, and zirconia infrastructures showed very similar results and created the lowest stresses in the cortical bone. However, the Cr-Co infrastructure showed the lowest stress values in the neck region of the implant and may be considered more advantageous than other infrastructure materials.

The elastic modulus and Poisson's ratio are material properties that determine flexibility and plasticity, influencing the extent of displacement under an applied force. In this study, in addition to the elastic modulus and Poisson's ratio of each simulated material, their density was considered to assess the impact of weight. As a result, the Cr-Co infrastructure exhibits an elastic modulus similar to that of zirconia, and in finite element analyses (FEA), these materials typically demonstrate comparable mechanical behavior.[24] However, Cr-Co has a higher density than zirconia, which contributes to an increase in the overall weight of the prosthesis when using this metal. In their study, Tribst et al.[14] argued that the heavier Cr-Co infrastructure model created more stress around the implant than the titanium infrastructure model. However, in the current study, the model with Cr-Co infrastructure created lower peri-implant stress values compared to the one made with zirconia.

It is crucial to recognize that all models simulate an all-on-four prosthesis supported by implants. In clinical scenarios involving tooth-supported prostheses, the presence of periodontal ligaments may modify the biomechanical responses to applied forces, leading to different bone deformation values in relation to Wolff's law. This is due to the fact that the periodontal ligament includes a robust cortical bone layer surrounding the connective tissues of the ligament fibers and permits micro-movements between each tooth abutment.[25,26] These structures differ significantly from the bone/implant interface modeled in this study. As a result, under identical compressive forces, tooth abutments may exhibit lower bone

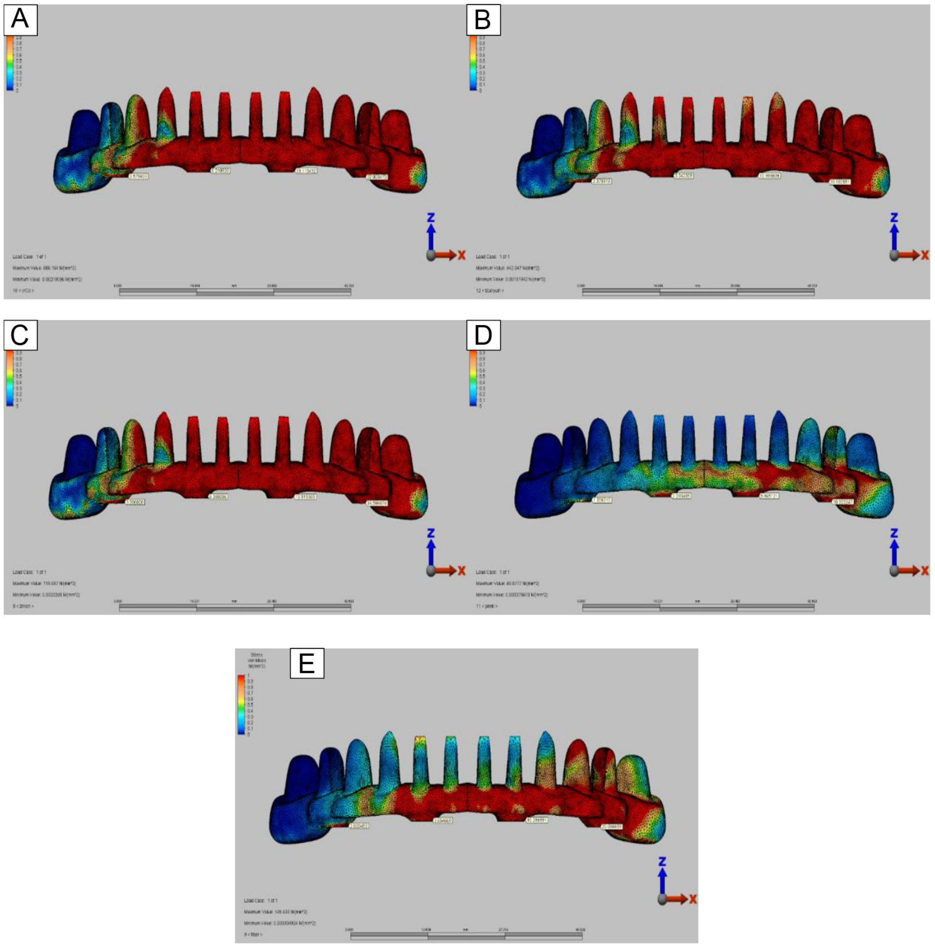

Figure 5. Von mises stresses on infrastructures: (A) chromium-cobalt; (B) titanium; (C) zirconia; (D) polyetheretherketone; and (E) fiber.

deformation compared to implants.[25] Nevertheless, the compression dynamics of the periodontal ligaments enable orthodontic movements that vary depending on force and time.[26] Therefore, extrapolating these findings to tooth-supported prostheses is not advisable. Further research is needed to explore this area.

Previous studies have evaluated the Von Mises stresses occurring around implants without including the weight of the prosthesis.[6] It has been found that as the hardness of the material used in the prosthesis infrastructure increases, the stress in the infrastructure and screw will increase proportionally, while the stress around the implant will decrease proportionally to the hardness of the material.[6,27] In the current study, prosthesis weights were also included in addition to the mechanical properties of the materials. Similarly, when the stress levels around the implant were examined considering the infrastructure material, the highest Von Mises stresses were observed in fiber and PEEK infrastructures, while the lowest stresses were observed in Cr-Co and zirconia infrastructures.

While the infrastructure material is thought by some authors to influence the amounts of stress transferred to surrounding components,[6,28,29] others have stated that it does not have a significant effect.[30] Previous studies comparing PEEK with titanium and zirconia without including prosthesis weight showed higher stress concentrations within the infrastructure in harder materials like zirconia, with titanium as the subsequent choice.[6,28] Various authors have argued that the increased stiffness of the infrastructures, despite the increased stresses in the zirconium infrastructure, allows lower loads to be transferred to the implant and prosthesis components compared to less stiff ones, thus preventing prosthesis failure.[6,31,32] Sirandony et al.[33] also stated lower stress values in the infrastructure but higher stresses in the bone when PEEK material was used. Similarly, in this study, as the hardness of the material used in the infrastructure increased, the stress in the cortical bones decreased and the stress was listed from largest to smallest as PEEK, fiber, titanium, zirconia, and Cr-Co. As the hardness of the infrastructure material increases, the stress in the structure of the infrastructure also increases in the current study, and the stresses are listed from largest to smallest as zirconia, Cr-Co, titanium, fiber, and PEEK.

The key innovation of this study, compared to previous literature, lies in the simulation of forces that account for the impact of the prosthesis' structural weight on the bone tissue. The influence of gravity on the prosthesis persists throughout the patient's lifetime. The decision to simulate a mandibular prosthesis was made because gravity operates in the same direction as occlusal forces, and no prior studies have addressed this aspect in scientific literature.

In the study, clinical conditions were attempted to be imitated using mathematical models, and comparative and interpretative results were obtained. When performing FEA, the bone–implant connection was assumed to be 100%, and the models were completely homogeneous and isotropic. It is not possible to model the structures to be examined exactly as they are in the natural environment within a computer environment. Therefore, for the results obtained to be clinically acceptable, they must be supported by long-term clinical follow-up examining the effects that may occur on the supporting tissues.

Considering the limitations of this study, the following determinations can be drawn:

1. There is a negative correlation between the elastic modulus of the prosthesis and the stress in the bones around the implant. It can be said that as the elasticity modulus of the materials used as the infrastructure increases, the stress transmitted to the bones and the implant decreases.
2. It can be said that the use of elastic materials such as PEEK and fiber as infrastructures in prosthetic restorations to be made according to the all-on-four treatment concept is risky for long-term success, and the use of rigid materials such as Cr-Co, titanium, and zirconia is more appropriate.
3. It can be said that as the elasticity modulus of the materials used as the infrastructure increases, the stresses within the infrastructure itself increase.
4. All prosthesis weights, from the lightest design (29.9 g, PEEK) to the heaviest design (55.6 g, Cr-Co), did not create detrimental stress values that would impair bone remodeling.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Ethics Committee Approval: N/A.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – O.G., S.H.A.; Design – O.G.; Supervision – O.G., S.H.A.; Resources – O.G., S.H.A.; Materials – O.G., S.H.A.; Data Collection and/or Processing – O.G.; Analysis and/or Interpretation – O.G., S.H.A.; Literature Search – O.G.; Writing Manuscript – O.G.; Critical Review – O.G., S.H.A.

Declaration of Interests: The authors declare that they have no competing interests.

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