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PERI-IMPLANT STRESS DISTRIBUTION IN MANDIBULAR ALL-ON-4 PROSTHESES FABRICATED ON MULTI-UNIT ABUTMENTS WITH COBALT CHROMIUM FRAMEWORK VERSUS THOSE WITH ZIRCONIA FRAMEWORK: A 3D FINITE ELEMENT ANALYSIS

Ehab Nashaat*, Doaa Mahmoud Elkady**,
Mohamed Farouk Abdallah*** *and* Amal Swelem****

ABSTRACT

The purpose of this study was to assess the peri-implant stresses produced by cobalt chromium and zirconium frameworks for mandibular prosthesis using finite element analysis.

Materials and Methods: This investigation was performed using three-dimensional finite element models of an edentulous mandible restored with a prosthesis supported by four implants. While the posterior implants were positioned at the second premolar location with a -17degree distal angulation, the anterior implants were positioned vertically and bilaterally in the lateral-canine area. All of the implants had multi-unit abutments. For the first model, a zirconia framework was constructed, while a cobalt-chromium framework was envisaged for the second. The two models were utilized to assess directional deformation, maximum principal stresses, and Von Misses stresses.

Results: The Von Mises stress, maximum principal stress, and directional deformation were assessed in the peri-implant bone area. Cobalt chromium and Zirconium frameworks showed non-significant difference in Von Mies stresses on the screw-retained prothesis to the underlying bone and implants.

Conclusion: Zirconium frameworks are comparable to cobalt-chromium frameworks as regards the stresses induced at the per-implant bone, they showed comparable deformation values at the fixation screws.

KEYWORDS: Bone-implant contact, Finite Element Analysis, Abutment angulation, Framework Design, All on four Concept.

* MSc, Implant Department, Faculty of Dentistry, Cairo University, Cairo, Egypt
** Lecturer of Prosthodontics, Faculty of Dentistry, Cairo University.
*** Professor, Department of Prosthodontics, Faculty of Dentistry, Cairo University, Professor, Department of Prosthodontics, Faculty of Dentistry, Galala University, Egypt
**** Professor of Prosthodontics, Faculty of Dentistry, Cairo University

INTRODUCTION

For many years, individuals who are edentulous have had the option of receiving treatment with conventional complete dentures. However, many patients experience problems when using their conventional dentures including instability, pain, and speech as well as chewing difficulties. Some of these problems may even affect the patient's quality of life leading to social, psychological and functional disabilities, a situation that can deteriorate further as the ridges resorb by time especially mandibular ridges (1).

Rehabilitation with implant prostheses serves as a valuable alternative in such cases and full arch implant supported restorations have now become a common treatment option with long-term efficiency (2). Numerous clinical trials supporting the predictability of implant-supported complete arch treatment reveal effectiveness and survival rates over 90% for several implant systems. But there have also been reports of some bone loss surrounding the implants that support these restorations (3).

Under the All-on 4 concept, immediate, provisional, or definitively restored removable or fixed prostheses are supported by four implants placed in the medial region of the mandible or maxilla. Two implants are positioned distally (17° to 45°) in the posterior portion of the alveolar ridge and two axially in the anterior region. This kind of treatment's predictability and safety have already been discussed in the literature (3).

In ALL-on-four implant-supported restorations it is advised to employ a framework that is used to attach artificial teeth. However the prosthetic framework's materials are crucial to its biomechanical performance. Materials including metals (such as Cobalt–chrome (CoCr) and Titanium), zirconia, and carbon fibers have been used for framework counterfeiting, and recently polyetheretherketone (PEEK) has also been introduced (4). Metal frameworks generally present good mechanical properties, however among all the available materials, alloys such as CoCr stand out and hence are widely used because they have an elastic modulus (>80 GPa) and tensile strength (>300 MPa) that are sufficient to avoid cantilever plastic deformation. The zirconia framework, which has outstanding mechanical and flexural strength and is biocompatible, would make a beautiful replacement. However, studies examining the load this substance imparts have yielded inconsistent findings (5).

MATERIALS AND METHODS

Three-dimensional modeling of the mandible

An edentulous mandible was scanned using cone beam computed tomography (CBCT), Materialize MIMICS software was used to construct a 3D surface model of the mandibular jaw. Anatomical structural segmentation was made possible by thresholding. In this investigation, compact and cancellous bones were examined. The three-dimensional reconstruction was exported as an STL binary file.

Bio-CAD modeling

The Reverse Engineering of STL: The MIMICS-based CT image segmentation approach resulted in two STL models, mentioning the cancellous and compact bones. After being further smoothed in **3-Matic Medical 11.0 (x64)** [1], these STLs were exported in STL formats. After being entered into the reverse engineering program **Geomagic Design x**[2], they were exported as solid components that could be assembled and subjected to Boolean subtraction in the **Ansys finite**[3] element analysis program.

Three- dimensional modeling of Implants and screws

An implant with dimensions of 4.1 mm in diameter and 10 mm in length was exported. as an STL file extension from the implant library of the Blueskybio program. The implant body's outer and inner shells were joined to form a bridge. Internal threads were then made to accept a screw with identical size and thread design. Finally, the implant body was solidified. The screw was exported as a solid file after becoming submerged in the Solidworks 2016 program.

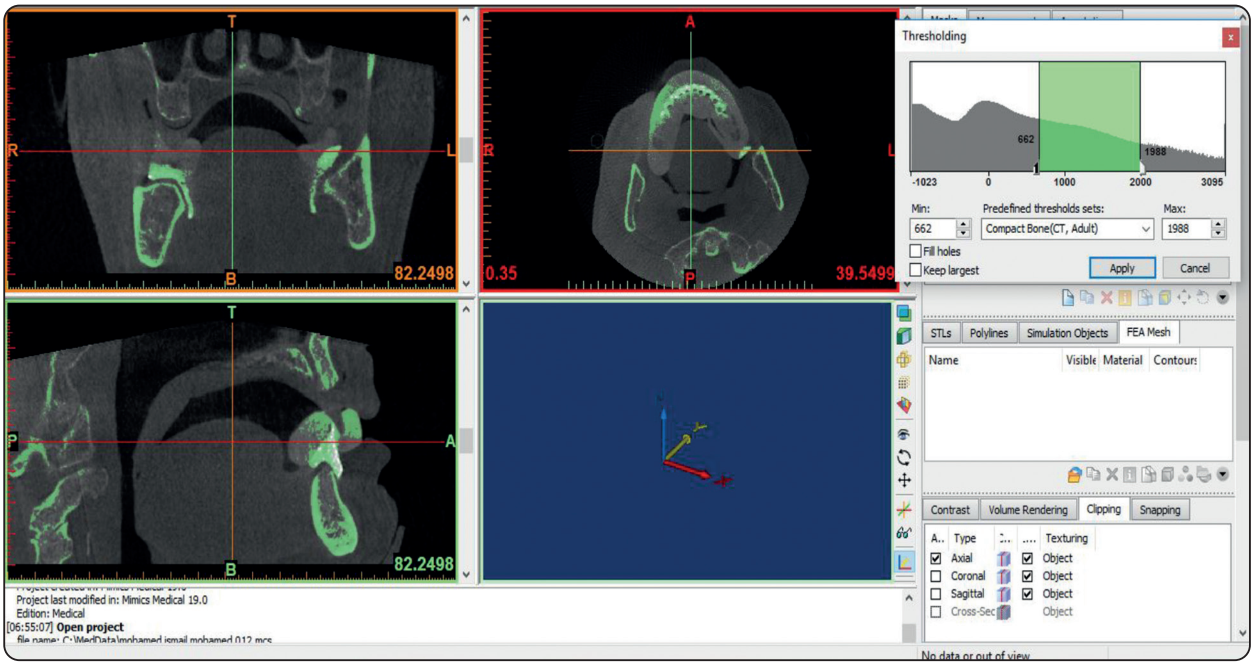

Fig. (1) Segmentation of anatomical structures of an edentulous mandible to generate a 3D surface model

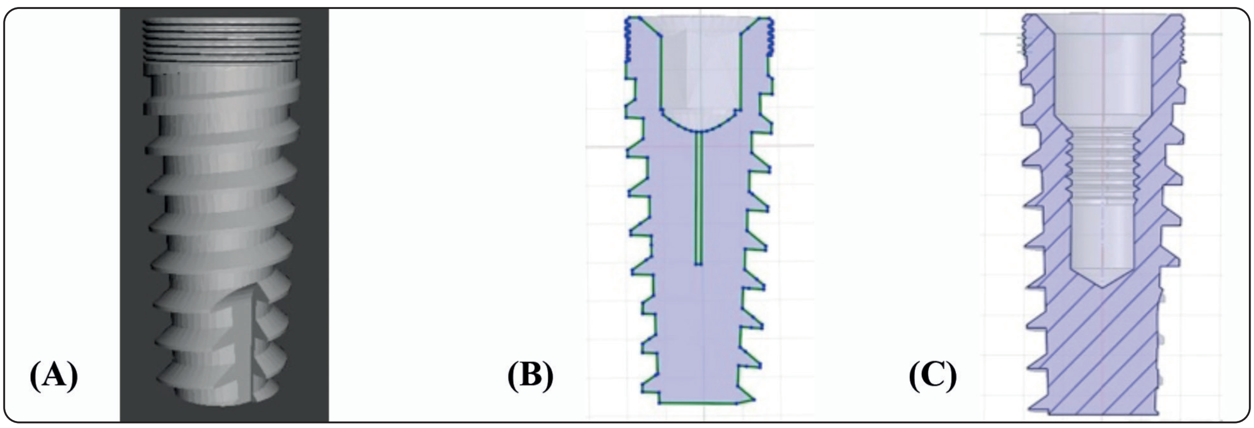

Fig. (2) A: Zimmer implant, B: Cross section before solid conversion, C: Cross section after solid conversion & thread incorporation

Assembling the components

Using an interference detection tool, Ansys software was used to import, assemble, and verify the presence of interference in all solid pieces. Initially, cancellous and compact bone segments were put together inside one another. Secondly, the computer-guided stent for each model was imported and positioned correctly on the compact bone. Thirdly, using the guiding stent holes, implants were introduced and positioned in each model at the appropriate angle and bone level. Subsequently, to precisely produce osteotomies, a Boolean subtraction of the implants from cancellous and compact bone was carried out.

Four inter-foraminal implants were positioned in each model; the anterior implants were positioned vertically in the lateral-canine area bilaterally, and the posterior implants were positioned in the second premolar region with a 17-degree distal angulation.

Every implant had a multi-unit abutment for both variants. A framework made of zirconia was made for the first model. **(Model A),** while for the second model a cobalt-chromium framework was planned **(Model B)**. The dimensions of the two frameworks were standardized in the two models. Both frameworks had a vertical width (thickness) of 3 mm and a cantilever length of 8 mm.

After the built framework was created and positioned correctly inside the implant's internal connection, anatomical acrylic teeth were used to cover the prosthesis. Ultimately, the screw components were used to tighten it, creating the finished product.

Defining the contact conditions

It was assumed that every contacting structure had 100% contact at the interface. The "contact/Gap" attribute was used to define the type of contact that existed between the components. Either "bonded" or "slip (no penetration)" connections were used to describe the contacts.

Bonded contact interface: This kind of contact was described as occurring between the implant and bony components, the gingiva and metal framework, and the cortical and cancellous bony sections.

Slip (no penetration) contact interface: This kind of contact was identified as being between the retaining screw complex, the metal framework, and the implant.

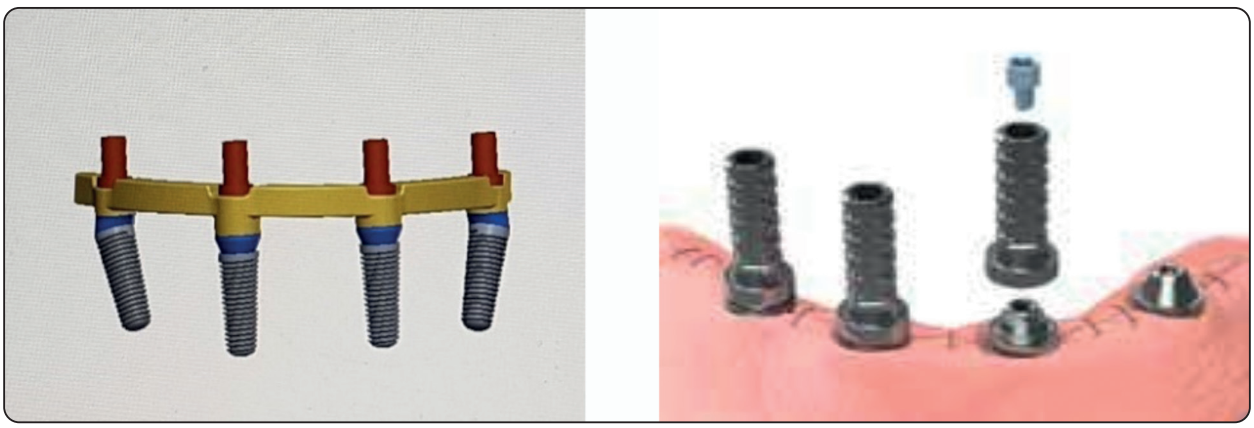

Fig (3) The framework splinting all four implanted implants through the multi-unit abutments, and the distal implants angulated at a 17-degree angle.

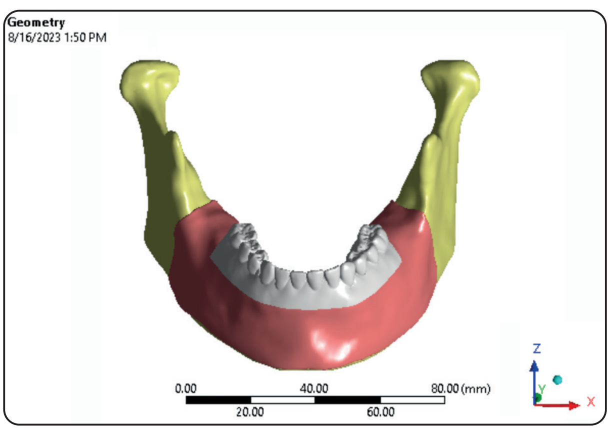

Fig. (4) The full mandibular model with the installed implants, framework and prosthesis assembly

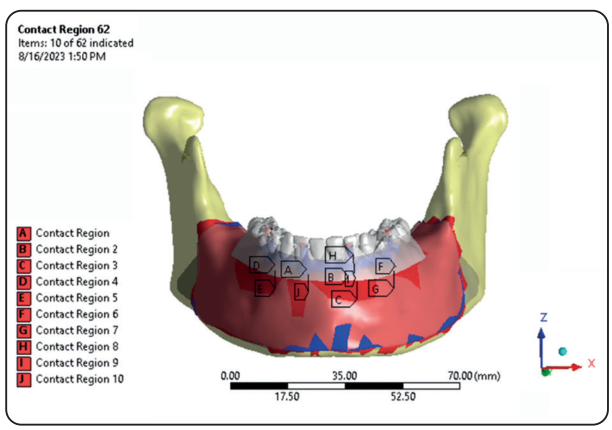

Fig (5) The bonded and slip contact interfaces for the full mandibular model.

Meshing

During this procedure, each model was broken up into tiny components known as elements, which were connected at sites known as nodes to build a mesh structure. Parabolic tetrahedral solid elements were used to build a fine solid mesh. Using a global element size of 0.9 mm and a tolerance value of 0.045, a straight forward unstructured tetrahedral mesh creation method designed for complicated geometries was applied. The variable mesh density was set to be lower than 0.2 mm element size around the implants and the peri-implant bone, which was then widened to reach a higher mesh density away from the areas of interest. Each framework's total number of components and nodes is stated in **Table (1)**.

TABLE (1) The sum of the elements and nodes for the zirconium framework and cobalt chromium framework

Model	Elements	Nodes
Mandibular frameworks (Zirconium)	853609	1398054
Mandibular frameworks (Cobalt chromium)	853609	1398054

In order to minimize file size and the time required to solve and complete the analysis, differential meshing was used. This involved limiting the mesh size around implants and the peri-implant bone and widening the mesh size away from the region of interests.

Defining the material properties

The program detected the material properties for each component, including the modulus of elasticity, compressive strength, yield strength, ultimate strength, and Poisson's ratio, based on data published in the literature **Table (2)**.

TABLE (2) The Poisson's ratio and modulus of elasticity for each component, including the cancellous and compact bone, as well as the two frameworks in use: Zirconium with Cobalt-Chromium

Material	Modulus of elasticity	Poisson's ratio
Compact bone	13700 MPa	0.3
Cancellous bone	7930 MPa	0.3
Gingiva	680 MPa	0.45
Cobalt-chromium alloy	200000 Mpa	0.29
Zirconium	200000 Mpa	0.3
Ti-6Al-4V alloy (Implant , Abutment and screw)	107200 Mpa	0.3
Acrylic resin (denture base)	3000 MPa	0.30

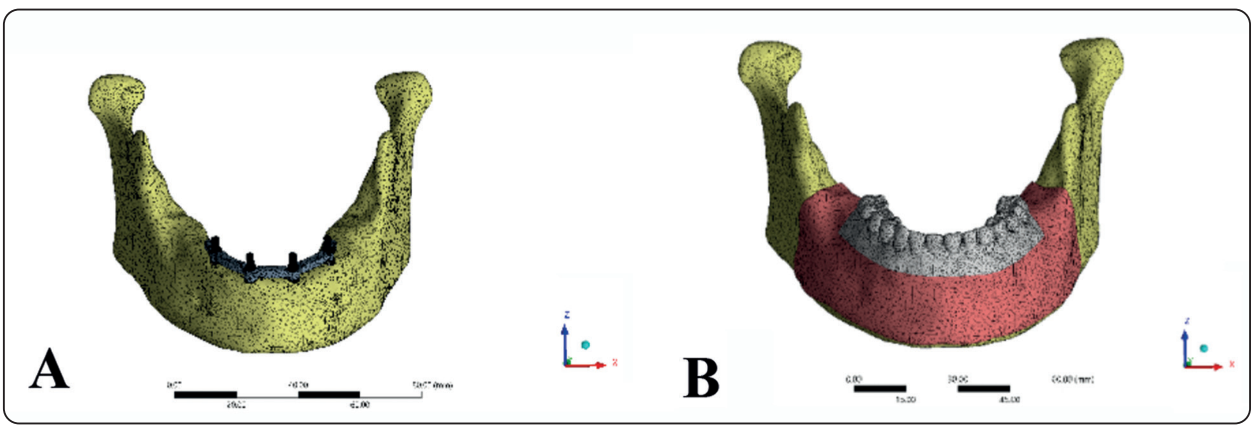

Fig. (6) Showing the mandibular all on four A) mandibular framework, B) Mandibular prosthesis after meshing

Defining loads and restraints

Initially, 30 Ncm of tightening tension was applied at the implant restoration interface using the "Bolt connector" characteristic., which tightened every screw on the implants. The titanium parts' defined coefficient of friction was 0.3220. The prosthesis was loaded bilaterally and vertically for every model and obliquely. A total of 400 N was loaded into each model (200 N on each side) by applying 100 N to the central fossae of the first molar and 50 N to the central fossae of each premolar. The force for oblique loading was applied at a 45-degree slant to the buccal cusps, including the central fossae. During the two loading simulations, the condylar constraints on both models were the same.

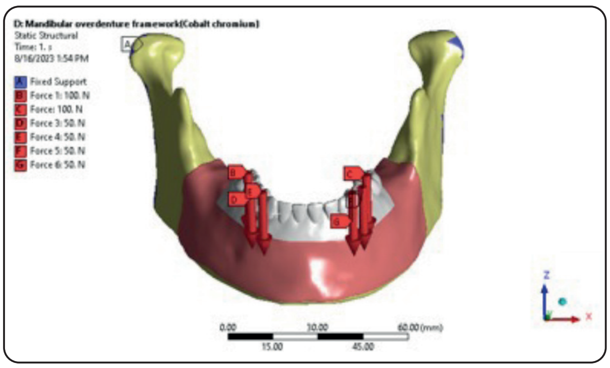

Fig. (7) Vertical loading in each model: 50 N on the two premolars (D - G) and 100 N bilaterally on the central fossae of the posterior teeth (B and C) on the first molar

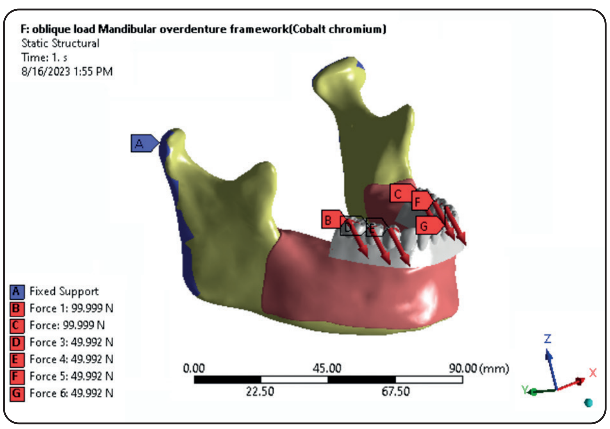

Fig. (8) Each model has oblique loading: 50 N on the two premolars (D - G) and 100 N vertically on the central fossae of the posterior teeth (B and C) on the first molar.

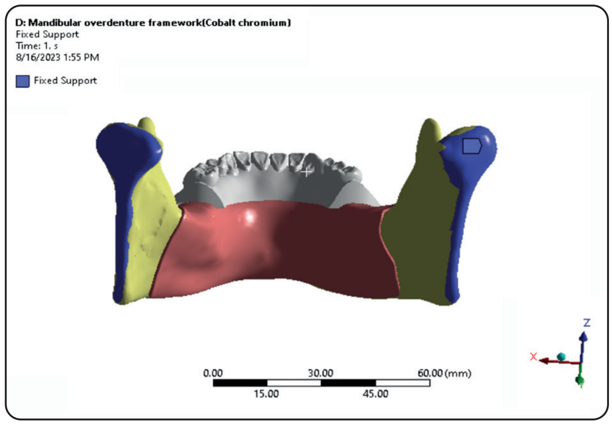

Fig (9) Condylar restraints.

Running of the analysis and collection of data

After meshing, the analysis was done iteratively to determine the stresses, strains, and displacements. Following the analytical procedure's conclusion, the maximum principal stresses were gathered at each model's peri-implant bone, while zones for multiple implants and multiunit abutments were examined to determine the maximal equivalent stresses, also known as von Misses stresses. The results were then compiled and compared.

RESULTS

The nodes of each model's stresses were identified using Finite Element Analysis. (FEA). Stress outlines were placed on the original model to show these findings. The models' computed numerical data for stress, deformation, and safety factors were used to create color visualizations. The applicable conditions' color coding is used to present the numerical values for the stress, deformation, and safety factor.

1. Maximum Principal Stresses (MPa) and directional deformation (Microns) in the two models:

Comparing model A with the zirconium framework to model B with the cobalt-chromium framework, For both loading scenarios, the former showed comparable maximum principal stress levels at the peri-implant bone and the same directional deformation. (oblique and vertical). However, upon switching from vertical (axial) loading to oblique loading, the maximum principal stress values in both models almost doubled. Under vertical loading, it was 15.611 for model A (with the Zirconium structure), while under oblique loading, it rose to 27.377. In a similar vein, under vertical loading, Model B (which has a cobalt-chromium framework) had a value of 15.607 and climbed to 27.366 under oblique loading **Table (3)**.

TABLE (3) Maximum primary stresses on the bone under vertical and oblique loading, as well as the direction of the bolts' deformation.

		Maximum principal stresses on bone (Mpa)	Directional deformation of bolts (microns)
Model based on the Framework Material	UNDER VERTICAL LOADING		
	Model A-Zirconium	15.611	5
	Model B-Cobalt chromium	15.607	5
	UNDER OBLIQUE LOADING		
	Model A-Zirconium	27.377	5
	Model B-Cobalt chromium	27.366	5

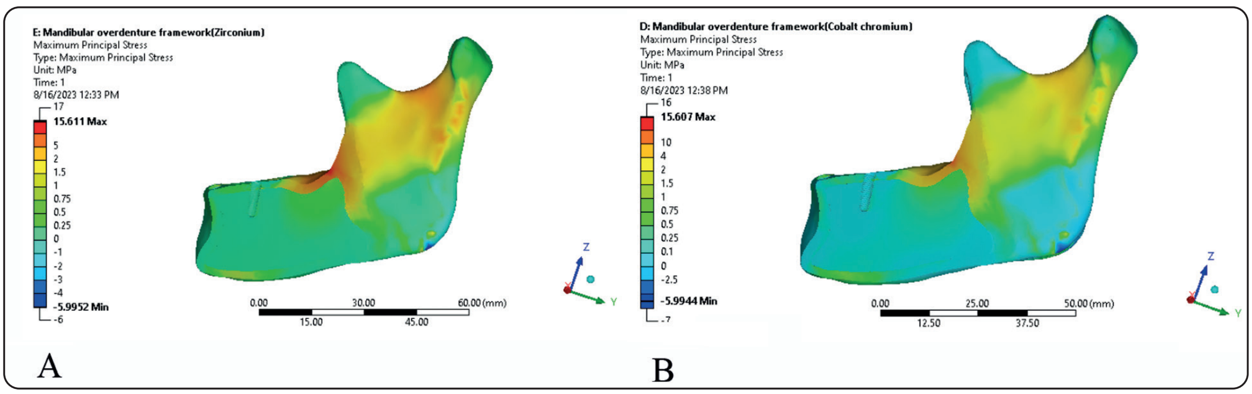

Fig (10) Maximum principal stresses in peri-implant bone under axial loading A: Model A: Zirconium framework, B: Model B: Cobalt chromium framework

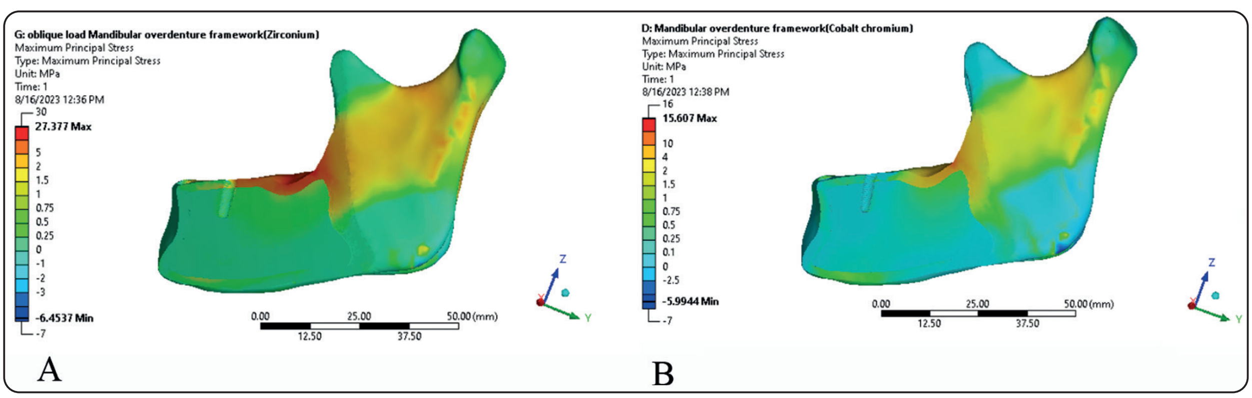

Fig (11) Maximum principal stresses in peri-implant bone under oblique loading A: Model A: Zirconium framework, B: Model B: Cobalt chromium framework

2- Von-Misses stresses on posterior and anterior implants and posterior and anterior multi-unit abutments for the two models

For vertical loading, model A with the zirconium framework showed the same stress distribution and comparable Von Misses stress values around implants and multi-unit abutments when compared to model B with the cobalt-chromium framework. However, for both models, the highest stresses were observed around the anterior implants and in the posterior multi-unit abutment **Table (4)**.

TABLE (4) The Von misses stresses (MPa) on implants and multi-unit abutments (right and left) in both models under axial loading

Axial Loading		Zirconium Framework (Model A)	Cobalt chromium Framework (Model B)
Posterior implant	Right (R)	38.112	38.125
	Left (L)	34.387	38.73
Anterior implant	Right (R)	38.726	34.386
	Left (L)	50.558	50.55
Posterior Multi-unit abutment	Right (R)	45.171	44.303
	Left (L)	61.319	61.148
Anterior Multi-unit abutment	Right (R)	41.735	41.695
	Left (L)	21.33	21.237

For oblique loading, model A with the zirconium framework showed the same stress distribution and comparable Von Misses stress values around implants and multi-unit abutments when compared to model B with the cobalt-chromium framework. However when posterior implants and multiunit abutments were compared to anterior implants and multi-unit abutments it was observed that, in both models with both framework materials, the posterior implants (both right and left) and posterior multi-unit abutments (both right and left) showed considerably higher VM stresses than the anterior implants (both right and left) and the anterior multi-unit abutments (both right and left) **Table (5)**.

TABLE (5) The Von misses stresses (MPa) on implants and multi-unit abutments (right and left) in both models under oblique loading

Oblique Loading		Zirconium Framework (Model A)	Cobalt chromium Framework (Model B)
Posterior implant	Right (R)	97.981	97.66
	Left (L)	92.119	92.047
Anterior implant	Right (R)	53.72	53.711
	Left (L)	80.355	80.357
Posterior Multi-unit abutment	Right (R)	112.82	112.48
	Left (L)	151.25	151.35
Anterior Multi-unit abutment	Right (R)	60.27	60.363
	Left (L)	38.308	38.434

DISCUSSION

Many stress analysis techniques have been used to investigate the biomechanical behavior of implant-supported prostheses and their contributions to the biomechanical assessment of oral rehabilitation utilizing dental implants. Among these methods is finite element analysis (FEA), Photo-elastic analysis, and the use of strain gauges. However, the current study employed the FEA for a number of reasons. The progressive resistance and stress distribution of intricate structures are tested and simulated by the FEA using virtual models. Therefore, biomechanical behavior of implants, bone, and prosthetic component interactions can be evaluated and simulated, which may be outside the scope of clinical analysis. Additionally, as was done in the current study, FEA allows researchers to apply various loading circumstances and determine the displacement and amounts of stress that this load places on the bone, implant, prosthesis, and teeth. In addition, the structures can be mechanically modeled in two or three dimensions. More consistent results can be produced by developing models that are more realistic and reflective of clinical circumstances, thanks to 3-D analysis[6]. A critical factor in finite element analysis is the interaction between the implant and bone. FEA software comes with a variety of contact algorithms that can mimic different sorts of real-world implant to bone contacts. However, FEA has many drawbacks, such as the presumption that all structures are homogenous, elastic, linear, and isotropic, but in reality, structures like bone are anisotropic, viscoelastic, and non-homogenous. As a result, care should still be used while interpreting FEA data[7].

The material qualities of implant fixtures, abutments, and restorations may have a major impact on stress and strain analysis. Because they affect accuracy, interfaces, loading conditions, and material qualities must be identified and taken into account for a FEA to yield trustworthy results that are clinically useful. Consequently, homogeneous, linear, and isotropic features of the material were assumed [8,9].

The von Misses stress, maximum and minimum principal stresses, and maximum and minimum principal strains are examples of common ways to display values from finite element analysis. The term “von Misses - Hencky criterion for ductile failure” (VMS) refers to the von Misses - Hencky theories. When an elastic body experiences a system of three-dimensional loads, a complicated three-dimensional system of stresses forms in the body. Stresses act in different directions at different points within the body, and these stressors differ in position and amount from one point to another. The von Misses criteria, a method for figuring out if the stress combination at a given place will produce failure, was applied by measuring the stresses on (multiunit abutments and implants) using the VMS. When the material’s “von-Misses Stress” surpasses its yield stress, it is considered to be in a failure condition [10].

As mentioned earlier, fabricating a framework for the artificial teeth to be attached to is crucial in implant-supported full-arch prostheses. For these frameworks, the alloy content should have high elastic modulus (more than 80 GPa) and tensile strength (more than 300 MPa), to avoid cantilever distortion. Cobalt chrome (CoCr) alloy is commonly used as a framework for this. However, Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) has been employed as a more aesthetically acceptable alternative to metallic frameworks with the development of CAD/CAM technology and rising demand for metal-free prostheses [11].

The dimensions of the two frameworks were standardized in the two models to exclude any other variable that may affect the study results. The vertical width (thickness) of both frameworks was designed so as to be 3 mm. As mentioned earlier, According to reports, in order to ensure adequate rigidity, cast alloy frameworks need to have a minimum of 3 mm of vertical bulk [12].

Both vertical and oblique loading simulations were performed in the current study. This was important so as to simulate as much as possible the clinical situation. Axial forces, bending moments, and stress gradients in the implant and bone are caused by the vertical and transverse forces that arise during mastication [13]. So, it was important to investigate if these different loading conditions will have an influential effect on the results.

Comparable results were observed for zirconium and cobalt-chromium frameworks with respect to the stresses at the peri-implant bone and the deformation values at the fixation screws. These results imply that these two materials seem to show similar biomechanical behavior under both vertical as well as oblique loading conditions. These findings are similar to those of previous studies(5,14). These studies attributed these findings to the stiffness of both materials.

Bhering et al., showed that stronger materials such as cobalt-chromium and zirconium, when compared to titanium, display similar biomechanical behavior and even better stress distribution. This is because they reduce displacement magnitudes and lower the stress levels in the abutments, screws, and bone (5). In contrast, **Topcu Ersöz et al.,** found that when using Zirconium frameworks instead of Cobalt-chromium frameworks, there were greater Von Mises stresses on the implant, implant screw, abutment, and prosthetic screws as well as higher maximum and lowest primary stresses in bone (15). These different findings may be attributed to the fact that their models simulated maxillary arches not mandibular arches as in this study. There have been reports that the mandible and maxilla have different physical characteristics of bone, such as modulus of elasticity. In general, the mandible's physical attributes are measured higher than those of the maxilla (16).

The current study showed that maximal principal stresses at the peri-implant bone were higher for posterior implants and posterior multi-unit abutments than for anterior implants and anterior multi-unit abutments, regardless of the framework material used. These results could be due to the angulation and tilting of the posterior implants. The present study's results are consistent with earlier research that found higher primary stresses with tilted posterior implants relative to axial/straight anterior implants (17,18). **Sannino.,** further stated that there was a direct correlation between the rise in stress concentration and the increase in the distal implants' tilt degree (angulation) (17).

The results of loading simulations showed that under oblique loading as opposed to vertical loading, both models' stress levels were higher. These findings align with the conclusions drawn by previous researchers (19,20,21). (**Geramizadeh et al 2016, Desai et al 2023, Yang et al 2023). Yang et al.,** stated that compared to vertical loading, oblique loading places more stress on the implant and mandible. This is an adverse loading condition. It has been reported that oblique loading is more detrimental to stress and strain distribution than axial loading. Such findings may imply that the direction of implant loading in an All-on-four fixed implant prosthesis may be more influential than the framework material used. Therefore, in the treatment planning phase, all factors that may increase oblique or lateral forces on the implants must be taken into consideration to minimize such forces as much as possible.

From the results obtained in the current study it could be assumed that frameworks constructed from Zirconium could maybe show comparable clinical outcomes as those constructed from cobalt-chromium as regards the amount of bone resorption around the implants, as well as comparable outcomes related to screw loosening or fracture.

CONCLUSION

Regarding All-in-four implant-supported fixed mandibular prostheses with 17° angulated distal (posterior) implants, the following findings may be drawn given the limitations of this in vitro investigation:

1. Zirconium frameworks are comparable to cobalt-chromium frameworks as regards the stresses induced at the per-implant bone, and they showed comparable deformation values at the fixation screws.
2. Oblique loading resulted in greater stress values than vertical loading regardless of the framework material used.
3. Stresses under oblique loading were greater for the posteriorly tilted implants and for the posterior multi-unit abutments as whatever kind of framework material utilized, in contrast to the prior multi-unit abutments and axially positioned anterior implants.

REFERENCES

1. McCord JF and Grant AA. Identification of complete denture problems: A summary. British Dental Journal. 2000;189(3):128–34.
2. Åstrand P, Ahlqvist J, Gunne J and Nilson H. Implant treatment of patients with Edentulous Jaws: A 20-year follow-up. Clinical Implant Dentistry and Related Research. 2008;10(4):207–17.
3. Lee DJ and Saponaro PC. Management of edentulous patients. Dental Clinics of North America. 2019; 63 (2):249–61.
4. Sugiura T, Yamamoto K, Horita S, Murakami K, Tsutsumi S and Kirita T. Effects of implant tilting and the loading direction on the displacement and micromotion of immediately loaded implants: An *in vitro* experiment and finite element analysis. Journal of Periodontal Implant Science. 2017; (4):251–8.
5. Bhering CL, Mesquita MF, Kemmoku DT, Noritomi PY, Consani RL and Barão VA. Comparison between all-on-four and all-on-six treatment concepts and framework material on stress distribution in atrophic maxilla: A prototyping guided 3D-FEA study. Materials Science and Engineering. 2016;69:715–25.
6. Pesqueira AA, Goiato MC, Filho HG, Monteiro DR, Santos DM and Haddad MF. Use of stress analysis methods to evaluate the biomechanics of oral rehabilitation with implants. Journal of Oral Implantology. 2014; 40(2):217–28.
7. Sertgöz A. Finite element analysis study of the effect of superstructure material on stress distribution in an implant-supported fixed prosthesis. International Journal Prosthodont. 1997;10(1):19-27.
8. Burak Özcelik T, Ersoy E, Yilmaz B. Biomechanical evaluation of tooth- and implant-supported fixed dental prostheses with various nonrigid connector positions: A finite element analysis. Journal of Prosthodontics. 2011; 20(1):16–28.
9. Huang HL, Hsu JT, Fuh LJ, Tu MG, Ko CC and Shen YW. Bone stress and interfacial sliding analysis of implant designs on an immediately loaded maxillary implant: A non-linear finite element study. Journal of Dentistry. 2008;36(6):409–17.
10. Christel P, Meunier A, Heller M, Torre JP and Peille CN. Mechanical properties and short-term in vivo evaluation of yttrium-oxide-partially-stabilized zirconia. Journal of Biomedical Materials Research. 1989; (1):45–61.
11. Tribst JPM, De Morais C, Alonso AA, Piva AMOD and Borges ALS. Comparative three-dimensional finite element analysis of implant-supported fixed complete arch mandibular prostheses in two materials. J Indian Prosthodont Soc. 2017;17(3):255-260.
12. Drago C and Howell K. Concepts for designing and fabricating metal implant frameworks for hybrid implant prostheses. J Prosthodont. 2012; 21(5):413-24.
13. Satyanarayana TS, Rai R, Subramanyam E, Illango T, Mutyala V and Akula R. Finite element analysis of stress concentration between surface coated implants and non-surface coated implants - An in vitro study. J Clinical Experimental Dent. 2019 1;11(8):e713-720.
14. Tribst JPM, Campanelli de Morais D, Melo de Matos JD, Lopes GDRS, Dal Piva AMO, Souto Borges AL, Bottino MA, Lanzotti A, Martorelli M and Ausiello P. Influence of Framework Material and Posterior Implant Angulation in Full-Arch All-on-4 Implant-Supported Prosthesis Stress Concentration. Dentistry Journal. 2022;10(1):12.
15. Topcu Ersöz MB and Mumcu E. Biomechanical investigation of maxillary implant-supported full-arch prostheses produced with different framework materials: a finite elements study. J Adv Prosthodont. 2022;14(6):346-359.
16. Seong WJ, Kim UK, Swift JQ, Heo YC, Hodges JS and Ko CC**.** Elastic properties and apparent density of human edentulous maxilla and mandible. Int J Oral Maxillofacial Surgery. 2009;38(10):1088-93.
17. Sannino G. All-on-4 concept: a 3-dimensional finite element analysis. J Oral Implantology. 2015;41(2):163-71
18. Deste G and Durkan R. Effects of all-on-four implant designs in mandible on implants and the surrounding bone: A 3-D finite element analysis. Niger J Clinical Practice. 2020 ;23(4):456-463.
19. Geramizadeh M, Katoozian H, Amid R and Kadkhodazadeh M. Static, dynamic, and fatigue finite element analysis of dental implants with different thread designs. Journal of Long-Term Effects of Medical Implants. 2016;26(4):347–55.
20. Desai SR, Koulgikar KD, Alqhtani NR, Alqahtani AR, Alqahtani AS and Alenazi A. Three-dimensional FEA analysis of the stress distribution on titanium and graphene frameworks supported by 3 or 6-implant models. Biomimetics. 2023;8(1):15.
21. Yang Y, Liu Y, Yuan X, Ren M, Chen X and Luo L. Three-dimensional finite element analysis of stress distribution on short implants with different bone conditions and osseointegration rates. BMC Oral Health. 2023;23(1)1-8.