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EFFECT OF ZIRCONIA, PEEK AND CFR-PEEK FRAMEWORKS VERSUS TITANIUM ON STRESS DISTRIBUTION OF ALL-ON-FOUR IMPLANT MANDIBULAR RESTORATIONS. A 3D FINITE ELEMENT ANALYSIS

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ABSTRACT

Background: The "All-on-four" concept for the treatment of edentulous arch consists of four implants that are put in between mental foramina; two mesial implants put perpendicular to the bone crest, and two distal implants installed inclined. The prosthetic framework material is a crucial parameter in stress concentration at the implants, framework, and the underlying bone.

Aim: The aim of the study is to evaluate the effect of Zirconia, Poly ether ether ketone (PEEK), and Carbon fiber reinforced poly ether ether ketone (CFR-PEEK) as framework materials compared to titanium framework in All-on-four implant-retained mandibular restorations.

Materials and Methods: The finite element model components were created on "Autodesk Inventor" Version 8 and were exported as STEP files, to be assembled and meshed in ANSYS environment. The model simulates a clinical situation where an edentulous mandible was restored with All-on-four restoration. Four different framework materials were tested; Titanium, Zirconia, PEEK and CFR-PEEK. A unilateral load of 200N was applied vertically and at 30º on distal implant as two loading cases.

Results: Von Mises stress for the Cortical bone was higher with PEEK framework 72 MPa followed by CFR-PEEK 68.5 MPa, Titanium 62 MPa and the least was the Zirconia framework 58 MPa in case of oblique loading. Zirconia framework showed the maximum Von Mises stress on the implant assembly 625 MPa followed by PEEK framework, CFR-PEEK framework and the least was the titanium framework 467 MPa.

Conclusion: Framework material has an effect on success of All-on-four prosthetic option. PEEK and CFR-PEEK frameworks should be applied with caution and need further research.

KEY WORDS: All-on-four, Titanium framework, Zirconia, PEEK, CFR-PEEK.

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INTRODUCTION

Implant retained restorations have become the most accepted treatment modality in prosthodontics. All-on-four implant system incorporates four implants placed in the anterior mandibular region between the mental foramina. Two mesial implants are put perpendicular to the bone crest, and two distal implants are installed inclined. The four implants are connected through a framework superstructure.[1] Material used in the construction of framework plays a major role in the biomechanical success of the restoration.[2]

Titanium is the material of choice in the dental field due to its superior mechanical properties and biocompatibility.[1, 2] Despite the several advantages of titanium, it has an esthetic concern due to its metallic color (greyish) and lack of light transmission which can provoke dark color of the peri-implant soft tissues and the restoration.[1-3] New tooth colored materials for implants and frameworks have emerged as an alternative to titanium. Zirconia a high-strength ceramic and poly-ether-ether- Ketone (PEEK) composites. Zirconia appears to be a suitable material for dental implants and frameworks due to its tooth-like color, excellent mechanical properties, and biocompatibility. The use of zirconia permits framework masking and presents a similar survival rate to metal.[3-7]

PEEK is a high-temperature thermoplastic polymers, containing an aromatic backbone molecular chain, interconnected by ketone and ether functional groups. PEEK has excellent characteristics including bio-compatibility, MRI compatibility, radiolucency on X-Ray, chemical resistance, adjustable mechanical performance and sterilization capability. The Young's modulus value of PEEK is similar to that of human bone thus, it is as elastic as bone.[7-11.] The mechanical properties of the PEEK material are improved by the addition of carbon fibers. Carbon fiber reinforced poly-ether-ether- Ketone (CFR-PEEK) is used as an implant and framework material compared to titanium.[12-14]

Studies have submitted that more rigid materials demonstrate elevated stress values in the prosthetic framework as compared to less rigid materials. Stiff materials have higher elastic modulus which will resist their deformation, thus increasing the stress concentration on adjacent structures. The occlusal forces could be decreased with a framework material with a lower modulus of elasticity and also, may equally divide the load. However, it has also been noticed that more rigid materials transfer less stresses to other components of the system. These biomechanical complications can worsen the osseointegration of implants and elicit bone resorption.[10, 15, 16.]

A major factor for the success or failure of implant restoration is how stresses are transferred to the surrounding bone. [17] Researchers are able to predict stress distributions in the contact area of an implant with cortical bone and around the apex of an implant in trabecular bone by The Finite Element Analysis (FEA). The FEA has shown to be an effective tool for evaluating the biomechanical properties of dental implants. The magnitude, direction, and duration of load employed on the implant play a major role in the dissipation of forces from the restoration into the surrounding bone. The 3D models represent the biomechanical interactions of the human anatomy, restorations, and implant components as a complex and are superior to 2D models. Some norms impact the exactness of the FEA results significantly. This includes detailed geometry of the bone and implant to be modeled, material properties, boundary conditions, and the interface between bone and implant[18, 19.] The aim of the study is to evaluate the effect of Zirconia, PEEK, and CFR-PEEK as framework materials compared to titanium framework in All-on-four implant-retained mandibular restorations.

MATERIALS AND METHODS

The finite element model components were created on “Autodesk Inventor” Version 8 (Autodesk Inc., San Rafael, CA, USA) and were exported as STEP files, to be assembled and meshed in ANSYS environment (ANSYS Inc., Canonsburg, PA, USA)(Figure 1). The model was prepared based on previous studies and simulates a clinical situation where an edentulous mandible was restored with All-on-four implant-retained mandibular restoration. The designs of the implant and the superstructure were taken from the manufacturer’s data. The system analyzed in this investigation consisted of the commonly available root form threaded titanium dental implant of

11.5mm length and 4.0mm diameter (Neobiotech Co., Ltd., Los Angeles, CA, USA) were modeled and placed perfectly as two vertically in lateral incisor region, and two distally inclined implants (30°) and placed anterior to the mental foramen. Whilst, ideal osseointegration, was supposed to be presented between implants and bone.

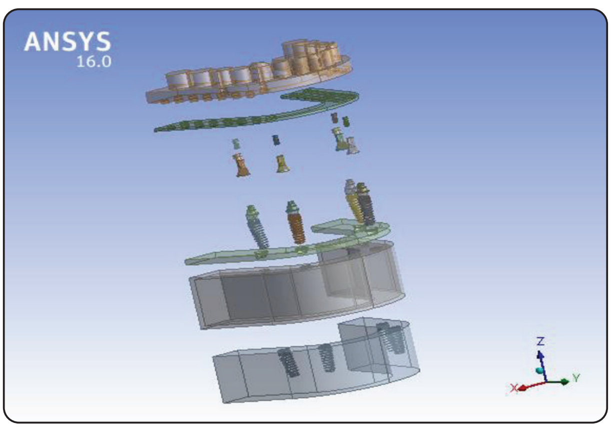

Fig. (1) Finite element model components

Four different framework materials were tested; Titanium, Zirconia, PEEK and CFR- PEEK. The simulated peri-implant bone comprised an inner layer indicating cancellous bone of 22 mm height and 14 mm width covered by an outer thin layer of cortical bone of 1 mm thickness. The simulated covering mucosal layer was of 1 mm thickness [19-21]. All materials to be used in this study were assumed to be homogenous, isotropic and linearly elastic and its properties are listed in Table 1. The meshing of the components was done by 3D solid element (SOLID187) which has three degrees of freedom. The lowest region of the cortical bone was set to be fixed in place as borders. A unilateral load of 200N was applied vertically and at 30º oblique on second pre-molar as two loading cases. Linear static analysis and solid modeling were performed on a personal computer Intel Core i7, processor 2.4 GHz, 6.0 GB RAM. The model was verified against similar studies and showed good matched results.[17-19]

Eight case studies (runs) were planned in this study as;

1. Model #1 with Zr Framework under vertival load of 200N
2. Model #1 with Ti Framework under vertival load of 200N
3. Model #1 with PEEK Framework under vertival load of 200N
4. Model #1 with CFR-PEEK Framework under vertival load of 200N
5. Model #1 with Zr Framework under oblique load of 200N
6. Model #1 with Ti Framework under oblique load of 200N
7. Model #1 with PEEK Framework under oblique load of 200N
8. Model #1 with CFR-PEEK Framework under oblique load of 200N

TABLE (1) Material properties

Part		Young's Modulous **Gpa**	Poisson's ratio **v**
Framework	Zr	200	31
	Ti	110	0.35
	PEEK	4	0.4
	CFR PEEK	15	0.39
Mucosa		0.01	0.4
Implants	Ti	110	0.35
Cortical bone		13.7	0.3
Spongy bone		1.37	0.3

RESULTS

Von Mises stress values on cortical bone were totally satisfying with vertical load application (Tables 2-5). In case of Titanium and zirconia frameworks, the cortical bone Von Mises stress reached 16 MPa which is safe from fatigue or yielding (about 120-150 MPa). In addition, levels of strain 968 and 1375 micro-strain reached remodeling levels (100 to 3000 micro- strain) that ensures good osseointegration between implants and cortical bone. In case of CFR- PEEK & PEEK frameworks, the von Mises stress values were slightly higher but within the safe range. (Figure 2)

Von Mises stress value on the framework varies according to the material tested. The highest value of Von Mises stress was observed with zirconia framework reaching about 108 MPa, it is still falling in the safe range under the Yield stress (about 850 MPa), and the fatigue limit (about 400 MPa) of zirconia. The titanium framework reached 76.61 MPa while the CFR-PEEK and PEEK frameworks showed a Von Mises Stress values of 29.72 and 16.27 MPa respectively. Deformations on mucosa appeared at the lingual side under the loading site with about 13 microns vertically and 13.1 microns as total deformation in case of zirconia framework. Von Mises stress was highest with PEEK framework 0.13 MPa.

Titanium implant which was located under the applied load received the highest stress level. The titanium framework presented Von Mises stress of about 244 Mpa that is lower than yield and fatigue limits of titanium which of order 680 and 330 MPa respectively. In case of Zirconia framework Von Mises stress was 233 MPa while for PEEK was around 200 MPa. In case of CFR-PEEK the stress on implant was 208.62 MPa. (Figure 3). Spongy bone showed very low levels of stresses and deformations, that cortical bone received most of the load energy and spongy bone work as cushion in case of the four framework materials.

TABLE (2) Summary of Run #1 results Ti Framework & 200N vertical load

R1	**Ti Framework + 200 N vertical loading**	
	Total Deformation	**Von Mises stress**
Part	**Mpa**	**Mpa**
Framework	0.01409	76.61
Mucosa	0.01376	0.10
Implants System	0.00910	243.56
Cortical bone	0.00685	15.98
Spongy bone	0.00645	3.21

TABLE (3) Summary of Run #2 results Zr Framework & 200N vertical load

R2	**Zr Framework + 200 N vertical loading**	
	Total Deformation	**Von Mises stress**
Part	**Mpa**	**Mpa**
Framework	0.01341	108.55
Mucosa	0.01310	0.09
Implants System	0.00894	232.22
Cortical bone	0.00681	15.79
Spongy bone	0.00642	3.19

TABLE (4) Summary of Run #3 results PEEK Framework & 200N vertical load

R3	PEEK Framework + 200 N vertical loading	
	Total Deformation	**Von Mises stress**
Part	**MPa**	**Mpa**
Framework	0.01829	16.27
Mucosa	0.01764	0.13
Implants System	0.01014	200.61
Cortical bone	0.00706	17.05
Spongy bone	0.00663	3.29

TABLE (5) Summary of Run #4 results CFR-PEEK Framework & 200Nvertical load

R4	CFR-PEEK Framework + 200N vertical Loading	
	Total Deformation	**Von Mises stress**
Part	**MPa**	**Mpa**
Framework	0.01659	29.72
Mucosa	0.01609	0.12
Implants System	0.00972	208.62
Cortical bone	0.00696	16.57
Spongy bone	0.00654	3.25

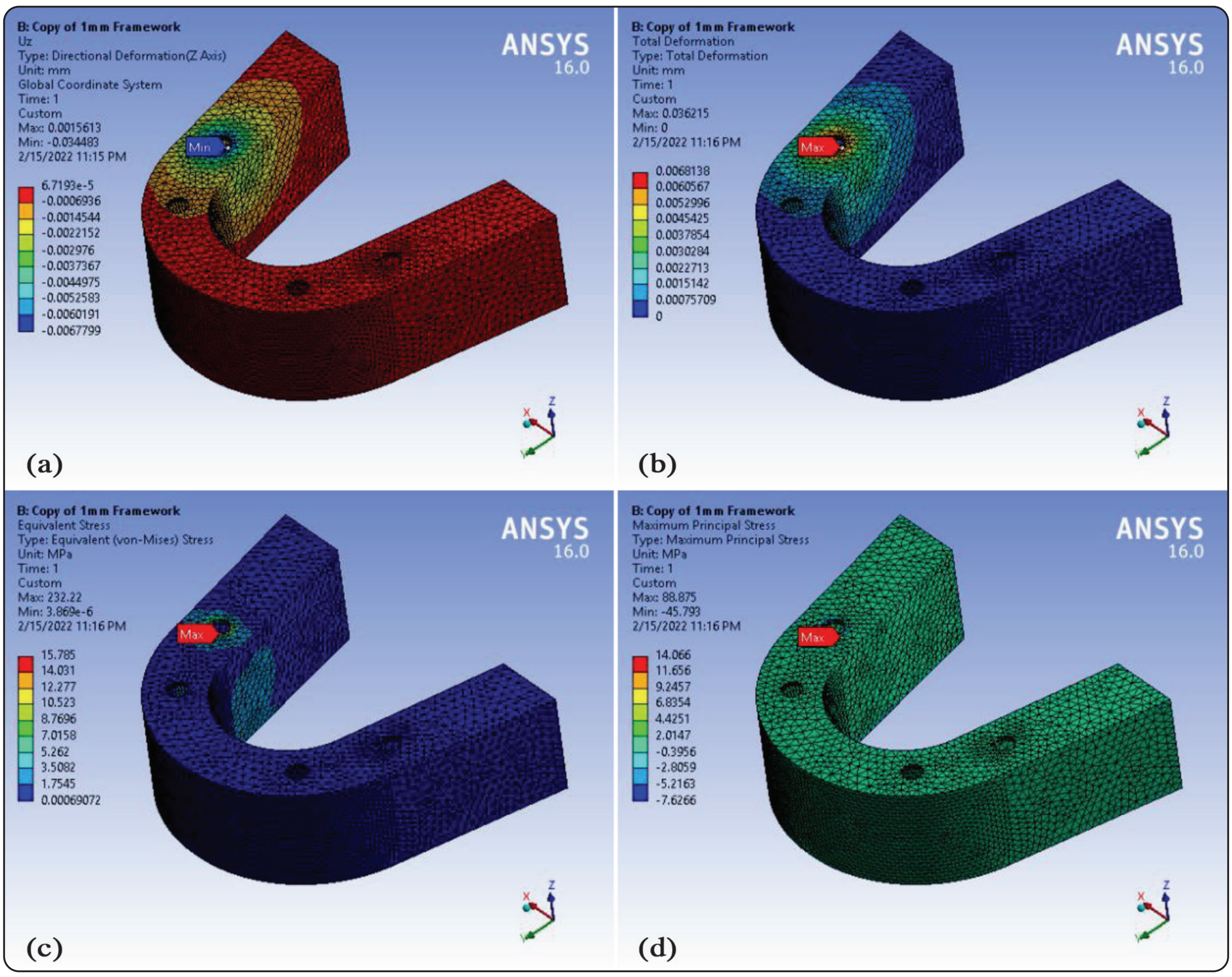

Fig. (2) Cortical bone results; (a) vertical deformation, (b) total deformation, (c) Von Mises stress,

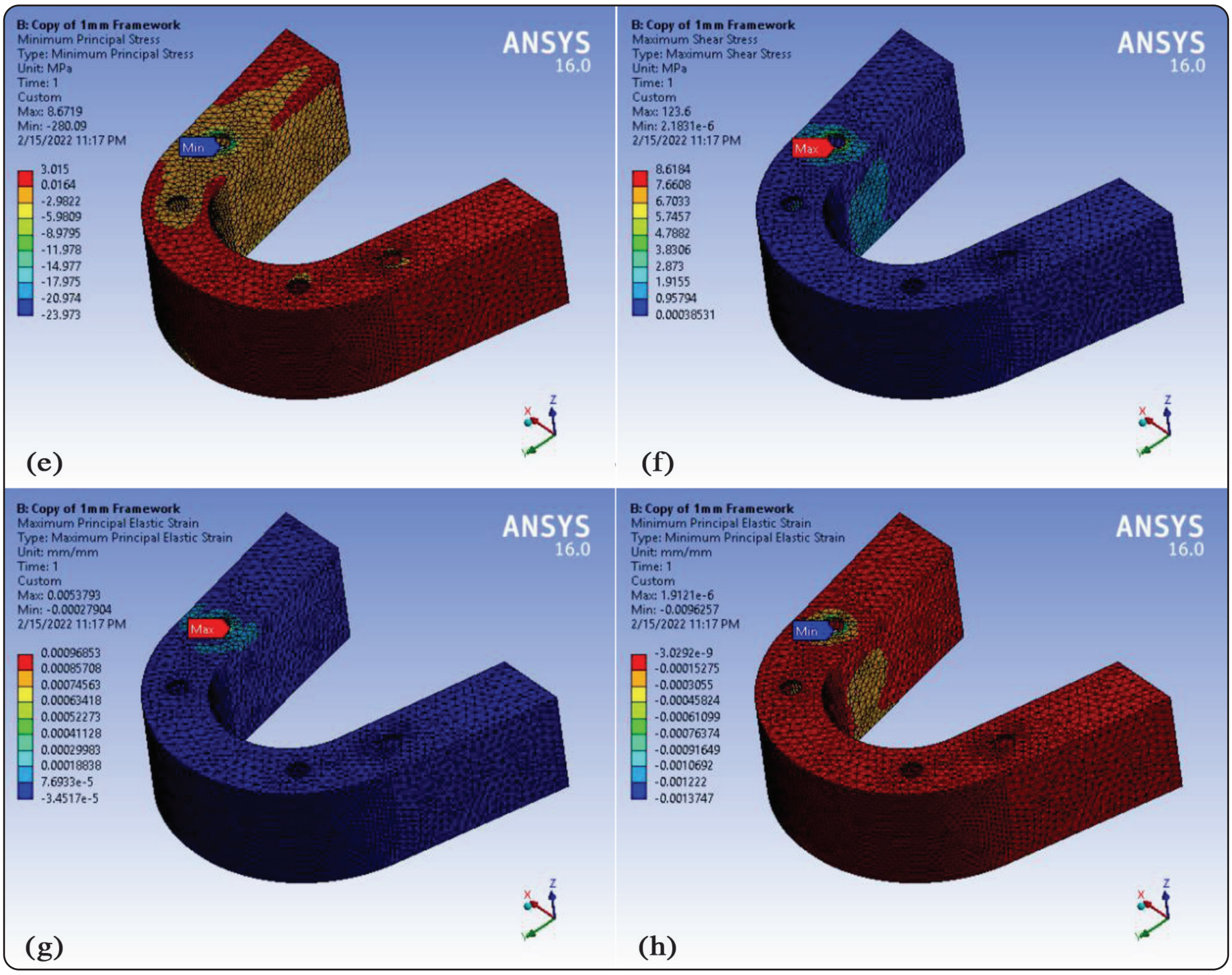

Fig. (2) Max principal stress, (e) Min principal stress, (f) shear stress, (g) Max tensile strain, and (h) Min compressive strain.

Von Mises stress values were higher on oblique loading than the vertical loading in case of the four framework materials (Tables 6-9). Von Mases stress values for the Cortical bone was higher with PEEK framework 72 MPa followed by CFR-PEEK framework 68.5 MPa, with titanium framework 62 MPa and the least was the zirconia framework 58 MPa in case of oblique loading.

Zirconia framework received the maximum stress compared to titanium and PEEK that reached 199 MPa while PEEK and CFR-PEEK received 41 MPa and 72.6MPa respectively. Von Mises values concerning the implant assembly was nearly doubled when compared to vertical load application. Zirconia as a framework material showed the maximum Von Mises stress on the implant assembly 625 MPa followed by PEEK framework, CFR-PEEK framework and the least was the titanium framework 467 MPa.

TABLE (6) Summary of Run #5 results Ti Framework & 200N oblique load

R5	Ti Framework + 200 N Oblique loading	
	Total Deformation	**Von Mises stress**
Part	**MPa**	**Mpa**
Framework	0.06484	175.40
Mucosa	0.06044	0.41
Implants System	0.05792	466.73
Cortical bone	0.01920	61.57
Spongy bone	0.01652	5.58

TABLE (7) Summary of Run #6 results Zr Framework & 200N oblique load

R6	Zr Framework + 200 N Oblique loading	
	Total Deformation	**Von Mises stress**
Part	**MPa**	**Mpa**
Framework	0.06083	198.22
Mucosa	0.05672	0.39
Implants System	0.05412	624.61
Cortical bone	0.01791	58.44
Spongy bone	0.01538	5.39

TABLE (8) Summary of Run #7 results PEEK Framework & 200N oblique load

R7	PEEK Framework + 200N Oblique Loading	
	Total Deformation	**Von Mises stress**
Part	**MPa**	**Mpa**
Framework	0.07323	40.48
Mucosa	0.06786	0.45
Implants System	0.07092	519.61
Cortical bone	0.02273	71.96
Spongy bone	0.01952	6.05

TABLE (9) Summary of Run #8 results CFR-PEEK Framework & 200N oblique load

R8	CFR PEEK Framework + 200N Oblique Loading	
	Total Deformation	**Von Mises stress**
Part	**MPa**	**Mpa**
Framework	0.06930	72.61
Mucosa	0.06439	0.44
Implants System	0.06680	541.51
Cortical bone	0.02186	68.53
Spongy bone	0.01881	5.91

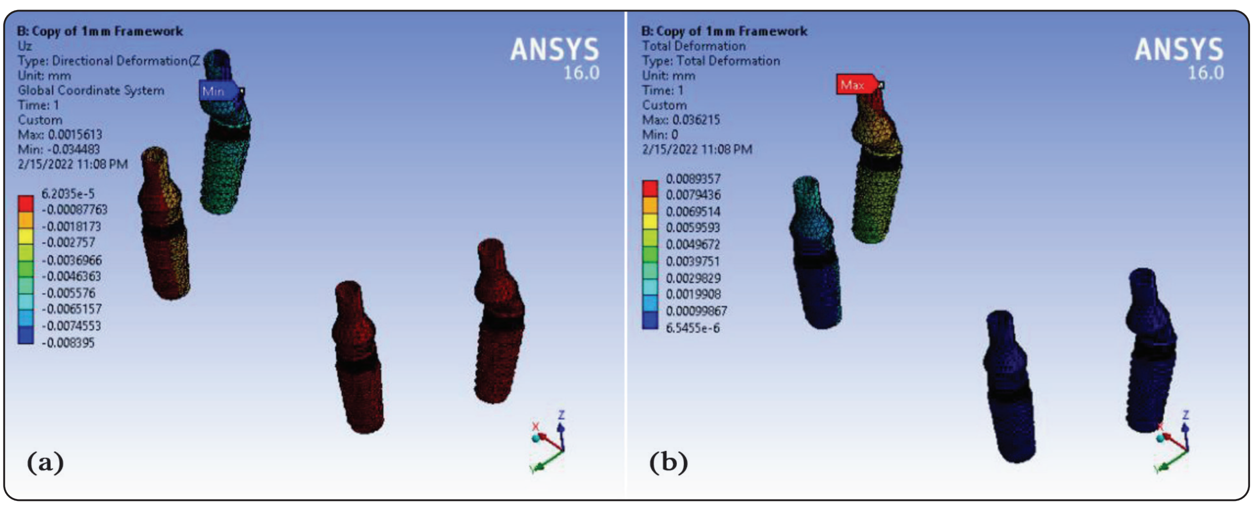

Fig. (3) Implant system results; (a) vertical deformation, (b) total deformation,

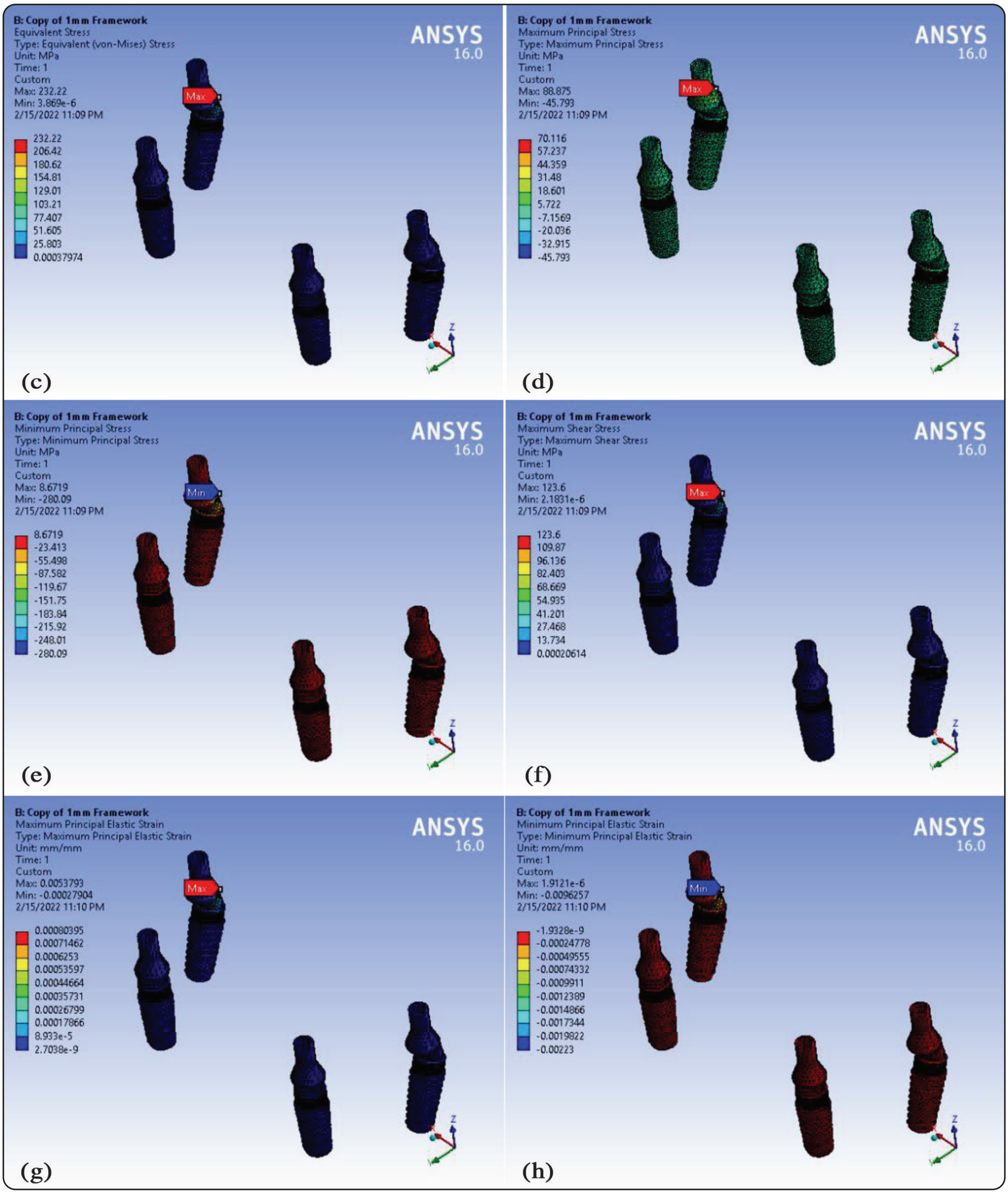

Fig. (3) (c) Von Mises stress, (d) Max principal stress, (e) Min principal stress, (f) shear stress, (g) Max tensile strain, and (h) Min compressive strain.

Upon vertical load application PEEK framework showed the highest total deformation when the four framework materials compared together while titanium and zirconia frameworks expressed higher Von Mises stress values as shown in figure 4. As we go away from loading points the differences in total deformation decreased. All stresses under vertical loading were within physiological limits, that no failure or fracture to be anticipated in any part of the model.

Total deformation and Von Mises stress values of oblique loading was much higher than vertical loading. Zirconia framework showed increased levels of Von Mises stress values when compared to titanium framework. CFR-PEEK framework presented higher values of Von Mises stress and lower values of total deformation when compared to PEEK framework as shown in (figure 5). Oblique loading cases showed higher level of differences between the four tested framework materials. In total deformation, PEEK framework and all underneath parts (structures), deformed more than titanium case, while zirconia framework case showed the lowest values. The mucosa and spongy bone showed safe levels of stress while cortical bone slightly exceed fatigue level zirconia was slightly better than titanium, and both were much better than PEEK and CFR- PEEK.

Additionally, the implant complex at the loading site showed very high Von Mises stresses close to titanium yield strength indicating a very short lifetime under such loading conditions.

Finally, the PEEK framework will fail under such oblique loading that its Von Mises stress exceeds the yield point.

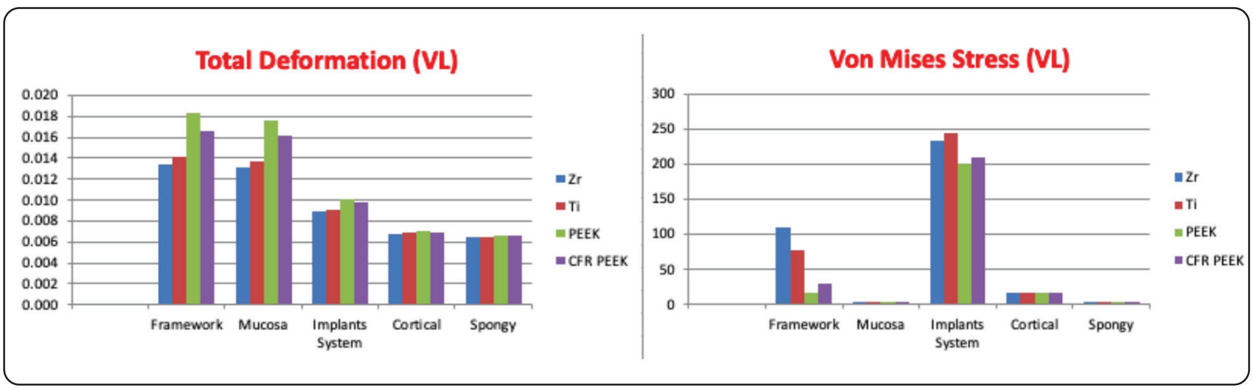

Fig. (4) Vertical loading cases comparison

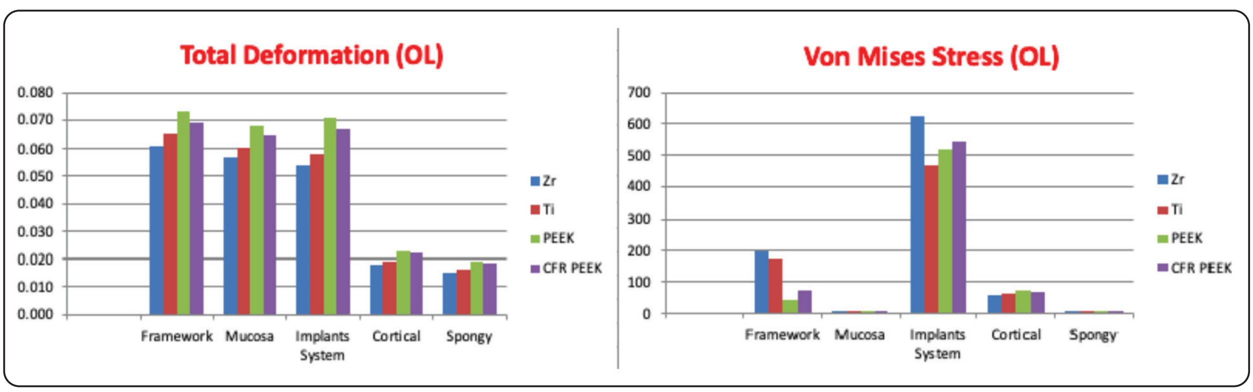

Fig. (5) Oblique loading cases comparison

DISCUSSION

This study evaluated the deformation and the stress distribution caused by four different framework materials in case of All-on-four mandibular implant restoration. A 3D model was used to achieve true-to-life results as the finite element analysis is a suitable scientific method for assessing biomechanical behavior in complex configurations. [19-21]

According to the literature, the vertical load in the molar region varies from 150 to 800 N, and there is a reduction of 30% to 40% when the load is applied unilaterally compared to bilateral applications[22-24]. In this study, the load was applied with 200 N reported as the mean value of occlusal forces in the posterior region in implant restorations.[1, 25, 26]

Deformation is the change in size or shape due to the application of force while the Von Mises stress is a value used to determine if a given material will yield or fracture. The Von Mises yield criterion states that if the Von Mises stress of a material under load is equal to or greater than the yield limit of the same material under simple tension then the material will yield.

The information of stress distribution around the implant-bone interface is critical for its long-range stability. The stresses transferred into the bone from different framework materials are divergent due to the variation in its Young's modulus of elasticity.[27-29]

The results presented in this study demonstrate that a flexible framework seems to increase stresses falling on implant assembly and cortical bone, especially on oblique loading. This finding is not following the suggested opinion that framework material has no effect on stress distribution[1.] A previous study[30] found that PEEK framework showed the highest stress peaks when compared with more stiff materials for the prosthetic screw. The present study agrees with this finding and suggests that further studies are necessary for evaluating screw performance. On the contrary, studies suggested that full-arch implant-supported fixed hybrid PEEK prostheses in the All-on-four concept may represent a valid treatment option[31, 32]. The authors reported prosthetic screw loosening in nearly 8-13% of cases that may be due to the increased stress. This can be explained as associated with the use of a flexible framework that is able to bend during chewing and able to stress the screw and bone, as shown in the present study.

CFR-PEEK is a variant of PEEK with an elastic modulus of 15 GPa which is near to that of bone. CFR-PEEK as a framework material will have a relatively short lifetime as its Von Mises stress was close to the yield point while PEEK failed under oblique loading. On the contrary, zirconia and titanium frameworks can survive under both types of loading for a long lifetime.

Titanium and CFR-PEEK implants produce similar stresses in bone as have researchers suggested. Thus, it can be used as a material of choice for implants and its suprastructures to reduce the stress concentration in bone.[10-12, 33] However, CFR-PEEK in this study presented higher stress concentration on bone due to the decreased stiffness and higher deformation in relation to the titanium. Thus, the increase in the elastic modulus of the framework material reduces the stresses transmitted to the implants and bone. This finding come in agreement with other studies which carry on nearly similar research.[34, 35]

Regarding the zirconia framework in case of oblique loading, the Von Mises stress values (624.61 MPa) were close to the yield point of titanium implants (680 MPa) which may indicate the implant's short lifetime. The continuous concentration of masticatory forces at a point on a dental implant for a long time may lead to implant failure. However, the zirconia framework when compared to titanium and PEEK in a Finite element analysis showed the least stress magnitude at the peri-implant region.[36]

In the present study, Titanium as a framework material proved to exert less stresses on implant assembly when compared to zirconia framework despite its higher young's modulus which is nearly double that of titanium. On the other hand, titanium showed more stresses on cortical bone compared to zirconia framework but both were within its physiologic limit.

The assumption that the materials being used have isotropic linear elasticity and inhomogeneity for bone is one of the limitations of the study. Despite not being seen in clinical settings, these are always present in finite element researches because of the shortcomings of biologic simulation. This study was performed under unilateral static loading. Although under different cyclic loading as those which occur during chewing, the framework materials may possibly behave differently. In order to assess and improve the relevance and the acceptance of the findings in the present study, further clinical studies are needed.

CONCLUSIONS

Within the limitation of this study, it is concluded that;

- Framework material has an effect on the success of All-on-four implant restoration.
- Titanium as a framework material exerts less stress on implant assembly when compared to the zirconia framework
- PEEK and CFR-PEEK should be applied clinically with caution in All-on-four implant restorations and need further research studies.

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