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Article

Effect of Different Dental Implants' Materials on Stresses Generated Around Implant-Supported Overdenture: A Validated 3D Finite Element Analysis

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ABSTRACT

Investigating stresses around various types of implants' materials in implant-supported overdentures is critical. The research question of the present study was will there be any difference regarding the stresses generated within and around all evaluated implant supporting an overdenture regardless of implants' materials?. Two-Polyetheretherketone (PEEK) implants were computer-aided designed and machined (CAD/CAM) as replica of titanium (Ti) implant. Epoxy-resin base and acrylic-resin overdenture-model was constructed. Computational 3D model of epoxy-base, implants' assemblies and overdenture were constructed with their exact dimensions using CAD software. Virtual vertical-static load of 100 N was applied on top surface of overdenture and resulting von Mises stress, resultant displacement and equivalent strain were recorded. For validation, the real model was subjected to same loading using universal testing machine. Afterwards, virtual vertical-static load of 120 N was applied and Finite Element Analysis (FEA) test was rerun for PEKK, Ti and zirconium implants. Validation results showed 27% difference in resultant displacement between FEA and mechanical models and 7% higher slope difference of linear portion of load/displacement curves in mechanical model. Regarding stresses generated in FEA models, for overdenture and base, maximum Von Mises stresses were found with PEEK implant. Our validated computational models allow further investigation of novel materials in implant manufacturing. Reduced stress-shielding effects of PEEK and PEKK implants models suggest these materials might improve surrounding tissues health leading to enhanced clinical outcomes.

Keywords: Validation, Finite Element Analysis, Dental Implants, Polyaryletherketone

1-Introduction

Implant-supported overdenture is a removable dental prosthesis retained by implants and can be used to treat both completely or partially edentulous patients. The use of implants to retain overdentures showed increased stability, support, and patient satisfaction by improving retention, pronunciation, and chewing ability. Furthermore, it reduces residual ridge resorption and is considered a less invasive and successful treatment option in terms of cost-effectiveness and durability. For these reasons, the McGill consensus concluded that "mandibular implant-supported overdentures should be the primary treatment choice for edentulous patients". [1-6]

Commercially pure titanium and its alloys are regarded as the "gold standard" material for dental implant fixtures due to its exceptional biocompatibility, high corrosion resistance, and strength. Titanium implants, on the other hand, have some potential drawbacks. For instance, metal ions release may cause bluish-grey discoloration, compromising esthetics, particularly, in areas with thin overlying mucosa. Furthermore, the elastic modulus of titanium and its alloys (110 GPa) are significantly higher than that of bone (5–30 GPa) resulting in a stress shielding effect. This results in less stresses being transferred to the bone tissue at the implant tissue interface as the implant absorbs the imposed loads and does not stimulate bone tissue, leading to peri-implant bone resorption and implant loosening.[7-12]

Ceramic implants have emerged as an alternative to titanium implants. Yttria partially-stabilized Tetragonal Zirconia Polycrystals (Y-TZP) have an inert nature, excellent biomechanical properties (flexural strength and fracture toughness), and an esthetic appearance. Furthermore, the low bacterial adhesion and low plaque adsorption on the implant surface are promising properties of zirconia implants, resulting in lower bone resorption rates. However, brittleness and low ductility have limited the widespread use of zirconia implants.[8-9, 12]

On the other hand, polymers have emerged as potential dental implant materials alternative to metallic implant materials, especially for patients who require metal-free restorations due to bruxism or allergic reactions. Polyaryletherketone (PAEK) is a crystalline polymer family that mainly includes polyetherketoneketone (PEKK), and polyetheretherketone (PEEK). PEEK, is a high-performance partially crystalline thermoplastic polymer that has been utilized in dental implantology since early 1998. PEEK offers several advantages over titanium and titanium alloys. PEEK's elastic modulus of 3.6 GPa, comparable to that of bone, provides for better force distribution around the implant and together with its low density, it lowers the stress shielding effect compared to dense titanium implants. PEKK and PEEK have similar chemical structures, however, compared to PEEK, PEKK has a second ketone group that allows for surface modifications improving its osseointegration. In addition, PEKK shows higher mechanical properties such as; flexure, tensile, and compressive strengths.[7-8, 11, 13-16]

It is critical to investigate the stresses generated and their distributions around various types of dental implants because improper stress distribution can result in mechanical failure of the implants. However, the biomechanical performance of implants cannot be tested in vivo due to difficulties in quantifying osseointegration, implant stability, and other factors. Several methods, including photoelastic studies, strain gauge, and finite element analysis (FEA), have been used to predict the values and distribution of stresses in the peri-implant region. FEA being the most precise among them. FEA is a widely used mathematical technique for predicting the biomechanical behavior of dental implants in vitro. It is widely recognized as a non-invasive and effective tool for determining stress distribution in the peri-implant area and around the components of implant-supported structures under simulated mechanical clinical conditions. Dental implants can be designed and tested virtually before being used in a clinical setting. This saves time, allows for the detection and correction of flaws, and prevents potential complications in the clinical setting.[4-5, 7, 9,17-19]

Therefore, this study aimed at comparing stresses generated within and around two emerging semicrystalline polymeric dental implants (PEEK and PEKK) to those generated within and around two widely used dental titanium and zirconium implants supporting an overdenture model. The research question of the present study was will there be any difference regarding the stresses generated within and around all evaluated implant supporting an overdenture regardless of implants' materials?. The null hypothesis of the present study was that there is no difference in the stresses generated within and around all evaluated implants supporting an overdenture regardless of implants' materials.

2. Experimental

The materials used in the current study were; Computer Aided Designing / Computer Aided Machining (CAD/CAM) PEEK (Brecam. BioHPP, Bredent Germany) machinable block, chemically cured epoxy resin and heat cured acrylic resin.

2.1. Preparation of real PEEK dental implants

The 3D computational implant model design was an exact replica to the design of titanium implant (Implant Direct™, USA) with dimensions of 10*3.7mm. The 3D model was created using CAD software, SolidWorks® Premium 2013 X64 Edition. The abutment portion was also 3D modeled as a direct attachment to the implant part, allowing both parts to be a single unit and will be referred to as "the implant assembly". The computational implant assembly model was then transferred as stereolithography (STL) file format to a five axis CAM milling machine (ED5X, Emar Mills, Egypt) where the PEEK block, was machined into the desired 3D real implant model.

2.2. Construction of real epoxy resin base model

Two implants' assemblies were fixed upside down using a modeling wax at the canine regions of a negative silicone model of a partially edentulous mandible, where all teeth other than canines' models were missing. The long axes of the assemblies were aligned along the long axes of the canines' negative models. The epoxy resin base and catalyst were proportioned and mixed according to the manufacturer's instructions and was poured into the silicone model from one side so that the mix had embedded the implants portions of the assemblies. A lab vibrator was used to vibrate the silicone model containing the freshly poured mix to get rid of air bubbles. The mix was then left to chemically set for 48 hours at temperature of 22 ± 2℃. The set epoxy resin base with the implants' assemblies was then removed from the silicone model. The exposed abutment portions were then cleaned up from the remnants of the fixing modeling wax.

2.3. Construction of real acrylic resin overdenture model

The epoxy base with the two implants' assembly's models was used to fabricate a lower heat cured acrylic resin denture in the form of heat cured occlusion block. This model was intentionally simplified to the occlusion block form to facilitate the process of the 3D FEA model validation as will be mentioned later as shown in Fig. 1

Fig. 1 The whole model of overdenture with two PEEK implants fixed in the epoxy base.

2.4. A computational 3D model construction and Validation of FEA model

A computational 3D model of epoxy base, implants' assemblies and the overdenture were constructed with their exact dimensions and relations using CAD software. The FEA simulator add in module in the same software was used for FEA. For simplicity, all materials were considered homogeneous linear elastic isotropic. The whole model was considered fixed at the bottom surface of the epoxy base. A compatible high mesh quality of 458172 total nodes and 323443 total elements was created. A virtual normal vertical static load of 100 N was applied to the top surface of the overdenture model.[20] and then simulator was run and the resulting von Mises stress (in MPa), resultant displacement (in mm) and equivalent strain were recorded.

For validation, the real mechanical model of epoxy base, PEEK implants' assemblies and overdenture was subjected to mechanical loading using a universal testing machine (Instron, Norwood, MA, USA) with a load cell of 5 kN controlled with a computer software (Instron® Bluehill Lite Software), Fig. 2. The load was applied vertically to the upper surface of the real overdenture with magnitude of 100 N at crosshead speed of 0.5 mm/min and the maximum displacement value was recorded and compared to the computational FEA resultant displacement under the same magnitude of applied load.[7] The slope of the resultant FEA load/displacement curve was also compared to the regression trend line of the linear part of real mechanical model load/ displacement curve as another method of validation.[21]

Fig. 2 The whole model tested by the universal testing machine.

2.5. FEA for virtual PEKK, titanium and zirconium implants:

After validation, a virtual normal vertical static load of 120 N was applied to the top surface of the overdenture model to simulate the actual oral masticatory forces [20] and the FEA test was then rerun for virtual PEKK, titanium and zirconium implants' materials of the same design to evaluate stresses generated within and around different implants' materials. The used mechanical values of the materials' properties are listed in **Error! Reference source not found.**.

Table 1 Mechanical properties' values of the used materials

	Elastic modulus (GPa)	Poisson's ratio	Compressive strength (MPa)	Mass density Kg/m^3	References
Epoxy	10.5	0.3	73.55	1150	[22]
Acrylic Resin	2.7	0.35	99.5	1051	[23-25],
PEEK	4.5	0.4	117.21	1329	[26-27]
PEKK	5.1	0.4	246	1300	[28- 29]
Titanium Alloy	113.8	0.34	1074	4420	[30-31]
Zirconium	94.5	0.34	2000	6530	[30, 32]

3-Results and Discussion

3.1. Validation of FEA model:

The maximum displacement mean of the whole model under 100 N vertical load of mechanical testing and the maximum FEA resultant displacement are listed in Table 3 and shown in Figs 3 & 4. The One hundred newton load produced resultant displacement value of 0.155 mm in the real mechanical model and 0.113 mm in the computational FEA model with percentage difference of 27%. The difference in the slopes of the linear portion of the load/displacement curves between the computational FEA and the real mechanical models were calculated and the resulting values were 884.96 and 949.23, respectively, with 7% higher slope difference in the real mechanical model.

Table 2 Resultant Displacement (mm) for computational FEA versus Real Mechanical Models.

	FEA	Mechanical testing	Difference (%)
Maximum vertical load (in N)	100	100	
Resultant displacement (in mm)	0.113	0.155	27%
Calculated slope values	884.96	949.23	7%

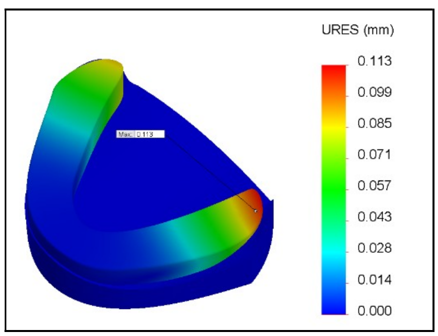

Fig. 3 Maximum displacement value of computational overdenture FEA model for validation supported with PEEK implants.

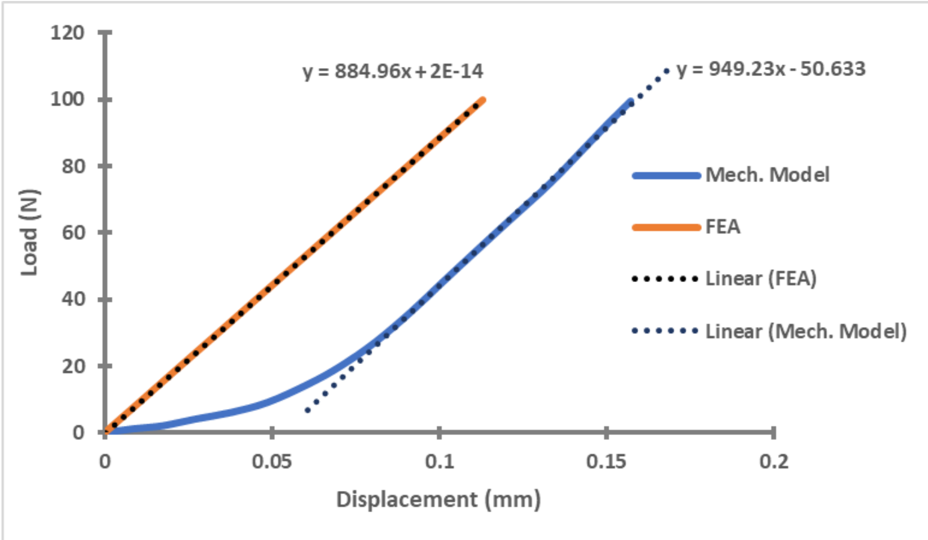

Fig. 4 Regression trend line of real mechanical model displacement under load of 100N compared to that of computational FEA model.

3.2. Stresses generated in the computational FEA model for different implants' materials:

Values of Von Mises stresses (in MPa) for different computational FEA models are listed in Table 3 and shown in Fig. 5. Regarding the overdenture, the maximum Von Mises stresses were found with the PEEK implant (36 MPa), followed by PEKK (35.1 MPa), then zirconia (25.3 MPa) and Titanium (25.2 MPa). For the implant assembly, the maximum Von Mises stresses were found with the Ti implant (52.4 MPa), followed by Zirconia (50 MPa), followed by PEKK (21.1 MPa) and PEEK (18.7 MPa).

Finally for the base, the maximum Von Mises stresses were found with the PEEK implant (34 MPa), followed by PEKK (31.9 MPa), then zirconia (17.1 MPa) and Titanium (16 MPa).

Table 3 Maximum Von Mises Stresses (MPa), Displacement (mm) & Equivalent strain generated in each part of different FEA models.

		PEEK	PEKK	Ti Alloy	Zirconia
Von Mises Stresses (MPa)	**Overdenture**	36.0	35.1	25.2	25.3
	Implants	18.7	21.1	52.4	50.0
	Base	34.0	31.9	16.0	17.1
Displacement (mm)	**Overdenture**	0.136	0.135	0.121	0.122
	Implants	0.005	0.005	0.001	0.001
	Base	0.002	0.002	0.001	0.001
Equivalent Strain	**Overdenture**	0.008	0.008	0.006	0.006
	Implants	0.002	0.002	0.000	0.000
	Base	0.001	0.001	0.001	0.001

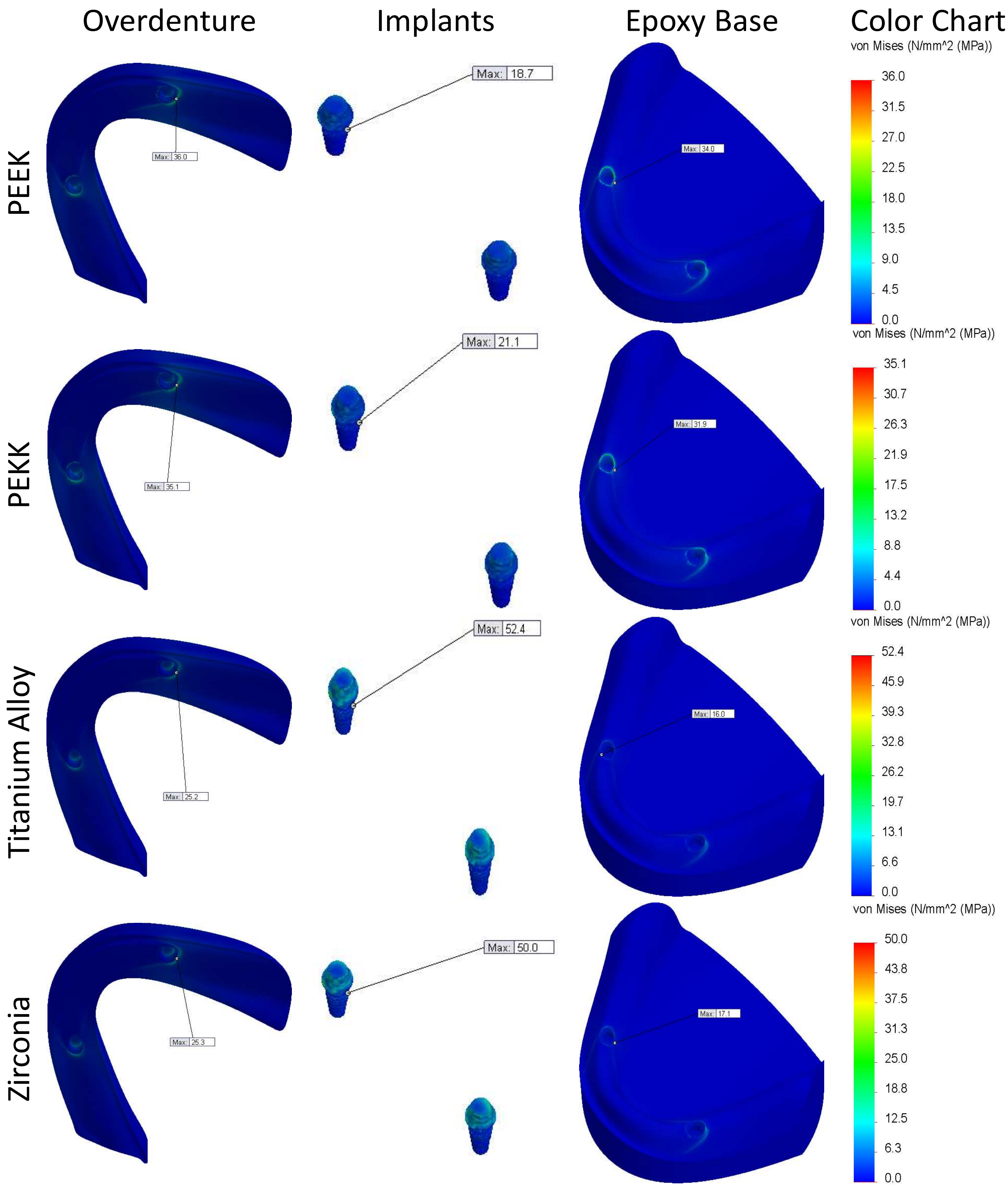

Fig. 5 Maximum generated Von Misses Stresses generated in the FEA models and their distributions.

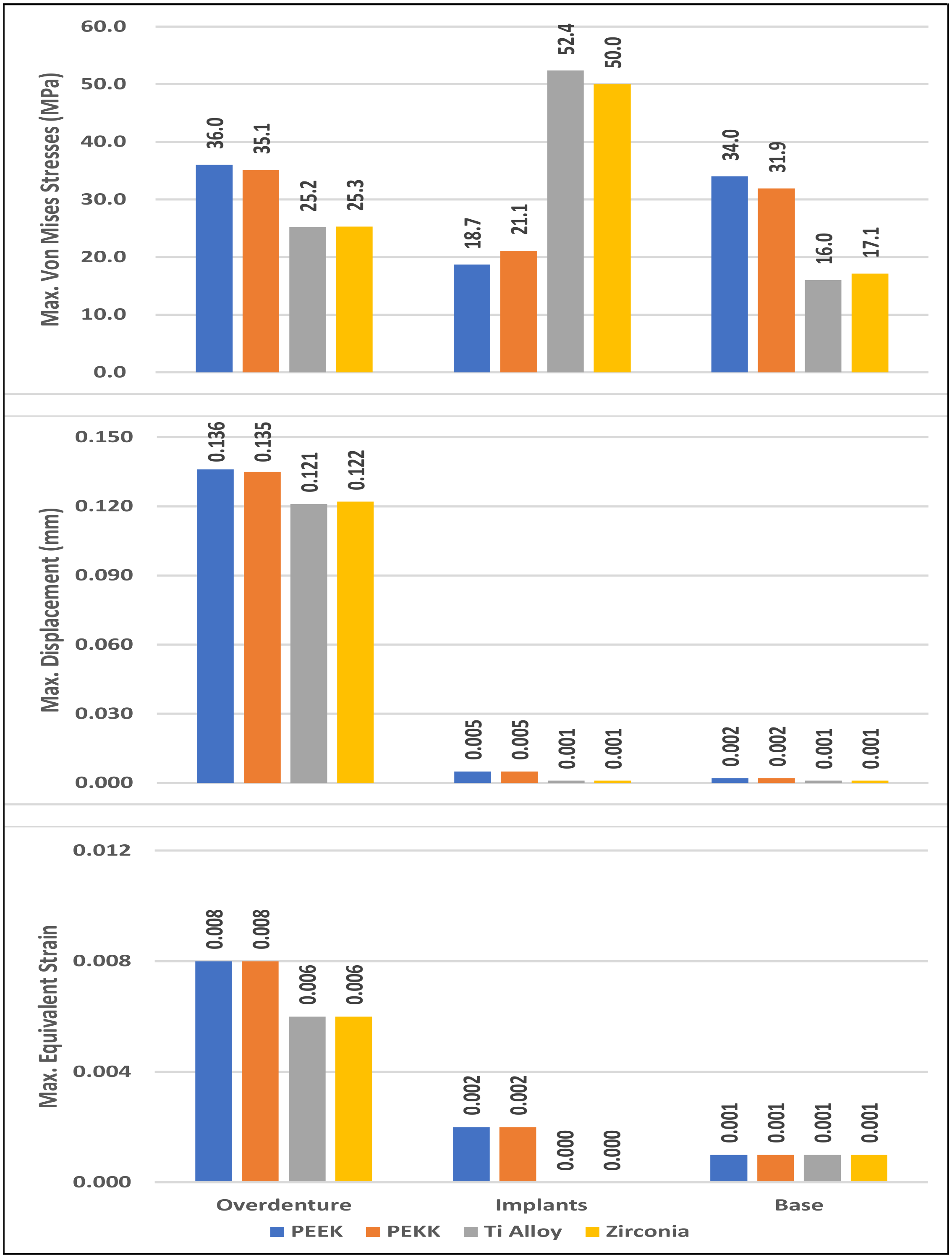

Fig. 6 Histogram showing Maximum Von Mises Stresses (MPa), Displacement (mm) & Equivalent strain generated in each part of different FEA models.

Discussion

Validation in computational solid mechanics was defined by the American Society of Mechanical Engineers Committee as "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model". This could be achieved by comparing results obtained from the computational FEA model to those from a real mechanical model. Hence, it could provide a method to compare and predict among further different models, which is the core purpose of FEA studies. Although validation of FEA studies is very important, yet it still be ignored in most dental implants FEA articles. Chang et al; 2018 reviewed validation processes in dental implant FEA studies, they found among 522 dental implants FEA studies, only 47 studies were made with validation; almost half of those articles were validated using models made of artificial materials.[7]

There are many levels for validation, the second top validation level of dental FEA implants studies is the comparison of the computational FEA model to a real mechanical experimental model. This is still true even if bone in mechanical and FEA models was replaced with artificial materials for simplicity. The techniques of mechanical models to compare with, may include; digital imaging, photoelastic stress analysis, strain gauge, fatigue testing and implant displacement under certain predetermined load. The later technique is a popular one and has been used by many researchers who validated their dental implants FEA studies. [7, 33-34]

In the current study, validation was done by two different methods; first, by comparing load – displacement curves of computational model to real model and secondly, by calculating the percentage difference of the regression coefficients of the straight-line slopes as shown in Fig. 4. Although displacement values were very small in both computational FEA model and the real mechanical model, yet, there was 23% difference between them, Table 2. This 23 % difference could be attributed to the very slight interfacial gap between the stiff overdenture from one side and the stiff epoxy base and implants on the other side within the real mechanical model. This minute gap allowed slight mobility of the overdenture that was reflected as a slight rocking and hence slight displacement during mechanical testing. However, during computational simulation, all parts of the computational model were designed to have intimate contact between them, which have resulted in a lower displacement value. This difference could be expected especially that the FE simulation model was completely designed by the aid of computer rather than being built up with the aid of CT scanning or other more precise similar methods. This was done for simplicity and to reduce geometric and calculation complexity.

Regarding the percentage difference of the regression coefficients of the straight portions of the resultant curves, Fig. 4, there was as low as 7% difference between slopes of both curves. According to Durand et al [21], less than 10% difference between slopes of computational FEA and real mechanical models is acceptable and the computational model is considered valid. Hence, our computational 100N loaded model of PEEK implants was considered valid and was used for further virtual comparisons with other implant materials and under other load values.

There is a wide difference in literatures on the maximum biting force values, whether in natural dentition or artificial appliances. Adopting 120N in the current study was based on the findings of Youssef (2022) study who found that the maximum recorded biting force exerted on 2 bilateral mandibular implant-supported overdenture at the canine regions was 116N. [20]

The values and distribution of maximum Von Mises stresses generated within other virtual computational FEA models are presented in Figs. 5 & 6. According to our results, all values of the generated Von Mieses stresses were much lower than the yield points of the tested materials, hence none of the tested materials would fail mechanically under 120N vertical load. Although the values of the stresses generated within PEEK and PEKK implants models were the least, yet stresses generated within their supported overdenture and epoxy base models were the highest, and the opposite was true for titanium alloy and zirconia implants models. This is likely owing to the simplified FE model that we used in the current study which assumes all materials to be homogeneous linear elastic isotropic.

This pattern was in accordance with findings of other studies, which showed higher stress values concentered in the surrounding structures around necks of implants, and their magnitudes were higher for implants with lower elastic modulus than around stiffer ones. [35-37]. This is considered of great importance for transmitting higher stresses to the peri-implant structures and therefore, reducing the stress shielding behavior of stiff implants on the surrounding bone tissues.

Since the results of the present study showed that there were differences in the stresses generated within and around all the evaluated implants' materials, therefore, we rejected the null hypothesis.

The FE analysis was simplified by simplifying the mechanical behavior of the materials studied by assuming that all materials were homogeneous linear elastic isotropic. Therefore, this study may not reflect actual clinical situations which is considered a limitation. Accordingly, further research should include more realistic material qualities like anisotropy, to have a better understanding of load distribution in an implant. Moreover, the fact that the validation in the current study was performed on a 3D model of a dental implant embedded in epoxy resin where bone structures and periodontal ligament were not simulated is considered a limitation. Another limitation is that the applied load in our FEA study was only vertical load which might not fully replicate the varied forces experienced in an actual oral environment, which can include non-axial forces in addition to vertical loads. Further research should investigate the effect of multi-directional loading conditions in the FEA to simulate the forces encountered during functional use, providing a more comprehensive understanding of implant performance.

4. Conclusion

Within the limitations of the current study, the following conclusions could be drawn:

- Our validated computational models allow further investigation of novel materials in dental implant manufacturing, highlighting the relevance of materials science in developing dental implants.

- The reduced stress shielding effects of PEEK and PEKK implants models suggest that these materials, from the mechanical point of view, might improve the health of surrounding tissues, potentially leading to enhanced clinical outcomes.

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- **Conflict of Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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