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Effect of prosthetic design and restorative material on the stress distribution of implant-supported 3-unit fixed partial dentures: 3D-FEA

Efeito do desenho protético e do material restaurador na distribuição de tensão de próteses parciais fixas de 3 elementos suportada por implante: FEA 3D

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ABSTRACT

Objective: Evaluate the effect of Implant prosthetic designs and restorative material on the stress concentration of 3-unit implant-supported restoration with two restorative materials. **Material and Methods:** Six different screw-retained prostheses models were virtually designed and divided according to design: fixed bridge (FB), cantilever bridge (CB), and separate crowns (SC). Then, each model was also divided into two subgroups according to the material: Ultra-translucent multi-layered zirconia (Kuraray Noritake Dental Inc., Japan); or a combination of PEEK (Polyetheretherketone) framework (BioHPP, Bredent, GmbH & Co., KG, Germany) and zirconia (ZR) crowns (ultra-translucent multi-layered zirconia, Kuraray Noritake Dental Inc., Japan). A vertical load of 100 N was applied statically perpendicular to the central fossa of each crown. The von-Mises stress was computed using Solidworks software (SolidWorks Corp, Massachusetts, USA), based on the physical parameters of the materials. **Results:** FB showed the lowest von Mises stress values out of all 3 design models. Moreover, the combination of PEEK and zirconia showed strain values smaller than full zirconia. The highest von Mises stress value was recorded in CB with the zirconia subgroup at (1098 MPa) while the lowest von Mises stress value was recorded in FB with combined PEEK and zirconia subgroup at (190 MPa). **Conclusion:** For three-unit implant supported restorations, the use of PEEK framework and zirconia crowns was found to be more favorable biomechanically regarding the prosthetic components, implant and bone stresses.

KEYWORDS

Biomechanics; Dental implants; Implant prosthetic designs; Finite element analysis; CAD/CAM.

RESUMO

Objetivo: Avaliar o efeito do desenho da prótese sobre implantes e do material restaurador na concentração de tensão de próteses fixas de 3 elementos implantossuportada, com dois materiais restauradores. **Material e Métodos:** Seis diferentes modelos de próteses aparafusadas foram virtualmente projetados e divididos de acordo com o desenho: ponte fixa (PF), ponte cantilever (PC) e coroas individuais (CI). Em seguida, cada modelo também foi dividido em dois subgrupos de acordo com o material: Zircônia multicamada ultra translúcida (Kuraray Noritake Dental Inc., Japão); ou associada a uma estrutura de PEEK (Polyetheretherketone) (BioHPP, Bredent, GmbH & Co., KG, Alemanha) e coroas de zircônia (CZ) (zircônia multicamada ultra translúcida, Kuraray Noritake Dental Inc., Japão). Uma carga vertical estática de 100 N foi aplicada perpendicular à fossa central de cada coroa. A tensão de von-Mises foi calculada usando o software Solidworks (SolidWorks Corp, Massachusetts, EUA), com base nos parâmetros físicos dos materiais. **Resultados:** PF apresentou os menores valores de tensão de von Mises de todos os 3 modelos propostos. Além disso, a combinação de PEEK e zircônia apresentou valores de deformação menores do que a zircônia pura. O maior valor de tensão de von Mises foi registrado em PC com o subgrupo de zircônia em (1098 MPa), enquanto o menor valor de tensão de von Mises foi registrado em PF com PEEK combinado e subgrupo de zircônia em (190 MPa). **Conclusão:** Para ponte fixa de 3 elementos implantossuportadas, o uso de estrutura PEEK e coroas de zircônia mostrou-se mais favorável biomecanicamente em relação aos componentes protéticos, implante e tensão sobre o osso.

PALAVRAS-CHAVE

Biomecânica; Implantes dentários; Desenhos protéticos sobre implantes; Análise de elementos finitos; CAD/CAM.

INTRODUCTION

Because implants lack periodontal ligaments and are in direct contact with the bone, they exhibit a biomechanical behaviors that differ from those of natural teeth. Consequently, the implant's occlusal load is directly transferred to the surrounding bone structure [1].

Many issues related to the excess load transferred to the implant may cause mechanical problems. Therefore the quantity and position of the implants in the arch can play a role [2]. Beyond the number of implants, these issues indicate that excessive force is dissipated in the bone around the implant. The type of connection between the abutment and implant, which can be internal or external, is an important parameter in the biomechanical behavior of implant-supported crowns. However, the optimum connection system is a point of ongoing research, Tribst et al. [3] evaluated the strain concentration in surrounding tissue and stress in the components of two implants with different prosthetic connections and suggested a better performance of Morse-taper implant connection.

Using photoelastic (PA) and strain gauge analysis, Assunção et al. [4] found that the number of implants had a direct impact on the distribution of strain.

In addition, when the prosthesis design changes, the biomechanics of the entire complex change, and the weakest component of the equation may alter. Investigators should therefore consider the pros and cons regarding cantilever extensions.

When an offset extension is used in the posterior region, a mesial location of the extension is advised to alleviate mechanical complications, and a minimal cantilever for a single unit has been recommended [5]. In contrast, a recent systematic review evaluating the survival rates of cantilever prostheses found that the survival rate was equivalent to that of prostheses with and without extensions. In addition, no severe adverse consequences, such as marginal bone loss, were observed [6].

In addition to the design, the restorative material is also important. Ceramic abutments have been developed to fulfil the rising demand for highly aesthetic results. Nonetheless, ceramics are naturally brittle, leaving them subject to tensile stresses. This prevents ceramics from being widely used in implant abutments [7].

Recently, ongoing research on materials with physicomechanical properties similar to those of natural teeth has introduced a new generation of high-performance polymers. The polyetheretherketone (PEEK) possesses excellent physical and mechanical shock-absorbing properties, with high biocompatibility for many applications [8].

A hybrid abutment crown is considered to be a custom abutment. It consists of a one-piece crown and abutment. Hybrid abutment crowns combine the mechanical reliability of the titanium base with the esthetic advantage of ceramics or zirconia. The titanium base has been suggested to provide a solution to improve the fracture resistance of zirconia, preventing mechanical fracture as well as implant-abutment connection wear [9,10].

Therefore various implant prosthetic designs in addition to materials have been suggested in the literature. Authors report that splinted crowns produce less peri-implant strain than non-splinted crowns. Furthermore, cement-retained crowns produce less peri-implant strain than screw-retained crowns [11]. Other investigation determined the shock-crushing effect of implant-supported restorations made of CAD/CAM composite resin [12].

Datte et al. [13] investigated the stress distribution in dental implants related to various restorative materials to aid clinicians in selecting the most appropriate restorative materials. The investigators discovered that materials with a high elastic modulus can reduce the stress values in abutments, implants, and peri-implant bones.

To date, there is no consensus in the literature regarding the ideal prosthetic design or which restorative material should be used to optimally restore multiple implants in a posterior edentulous area. The goal of this study was to assess how distinct implant prosthesis designs and materials affect the biomechanical behavior using 3D- finite element analysis. The null hypothesis was that different implant prosthesis designs would result in different outcomes. The second hypothesis was that prosthetic materials would not affect the biomechanical behavior at the prosthetic component, implant, and bone levels.

MATERIALS AND METHODS

Virtual prosthetic implant design was performed using a 3D model that simulated the mandibular bone using the 3D position implant planning software (3 tioLogic®). Implant fixtures selected from the library were virtually placed in the model, with parallelism to each other according to bone level.

Six different screw-retained 3D models were virtually designed and divided into three main groups: fixed bridge (FB), cantilever bridge (CB), and separate crowns (SC). The models were also assigned to two subgroups: subgroup I – Ultra-translucent multi-layered zirconia (Kuraray Noritake Dental Inc., Japan); and subgroup II – using a combination of PEEK framework (BioHPP, Bredent, GmbH & Co., KG, Germany) and zirconia crowns (ultra-translucent multi-layered zirconia, Kuraray Noritake Dental Inc., Japan), as shown in Figure 1.

Each model, were sent to SolidWorks (SolidWorks Corp, Massachusetts,USA) as DICOM files for solid digital structural evaluations. The

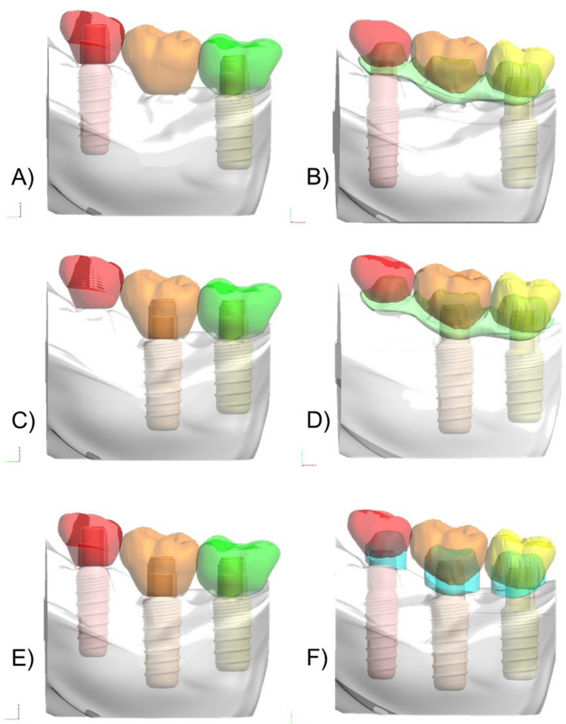

Figure 1 - Models simulated. (A) ZR bridge; (B) PEEK & ZR bridge; (C) Cantilever ZR bridge; (D) Cantilever PEEK & ZR; (E) separate ZR crowns; (F) Separate PEEK & ZR crowns.

geometry was constrained with its streamlined surfaces, to ensure a better quality of the mesh that was subsequently generated. The mesh was then used to fabricate three-dimensional mathematical models for the finite element analysis (FEA).

The bone was considered to be a single-volume structure. Furthermore, the implant and abutment were assumed to be made of titanium. The bone, implant, and abutment were assumed to be homogeneous, isotropic, and linearly elastic, and the 3D model of the implant was then placed in the bone structure with 100% osseointegration. A resin cement layer with a thickness of 30 mm was defined between the titanium-based abutment complex and the restoration, to simulate the adhesive luting.

Each model file of the designed restorations were transferred into 3 Matics for STL size reduction without affecting the quality, and the STL files were meshed using 3-matics. Three-dimensional finite element models were obtained and exported to finite element analysis software. Four-node tetrahedral elements were used for finite element modeling with a degree of freedom in the anterior-superior, axial, and anterior-posterior directions at each node. A quadratic interpolation function with 10 nodes, with each node having six degrees of freedom, was chosen because the function provides a closer approximation to real conditions and adapts to irregular meshes while maintaining their properties. The generated mesh contained 316,109 elements.

Additionally, the stress and strain in each direction were calculated at one integration point per element. The linear material properties were included in the generated finite element model.

Based on data from literature and assuming linear and homogeneous material behaviors, the mechanical characteristics of the elastic modulus and Poisson's ratio of various materials were included in the software, as listed in Table I [14].

The base of the bone can was restricted to only move in three longitudinal orientations and three rotational directions. The same constraints were applied to the bone ends, and because the geometry was asymmetric, one side of the bone

Table I - Bone, implant, and restorative material properties

Property	Bone	Implants	Zirconia	PEEK
Elastic modulus (GPa)	13.7	110	200	3.5
Poisson's Ratio	0.30	0.34	0.26	0.36

area was constrained to prevent axial load-induced distortion of the mandibular bone.

The implant and bone were in a state of contact along their borders. The interface between the implants and artificial mandibular bones had a coefficient of friction of zero. The contact model of the FEA was utilized to replicate the boundary conditions of the experimental model, and all tooth shapes and materials employed in the model were assumed to be isotropic, elastic, linear, and homogenous.

The location and direction of load prescription were determined to be in the central fossa of each crown, and a load of 100 N was applied perpendicular in a vertical direction. Based on the physical parameters of the materials, the stress levels (von Mises stress) in the implant, peri-implant bone, and restorations were computed (Figure 2).

RESULTS

The maximum stress (equivalent von Mises stress) for each subgroup was located in the implant, and the stress distribution was presented, as shown in Figure 3. In all models, all implant stresses were localized on the cervical region. However, the maximum von Mises stresses in the cantilever group appeared to be larger than those in the other groups, with the highest values in the zirconia cantilever model.

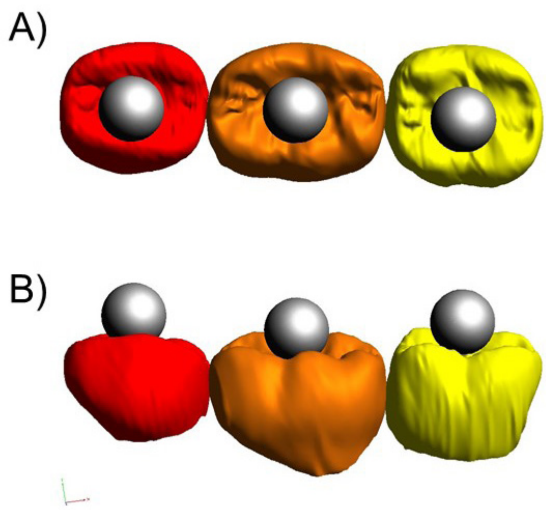

Figure 2 - Load application in (A) frontal view and (B) occlusal view.

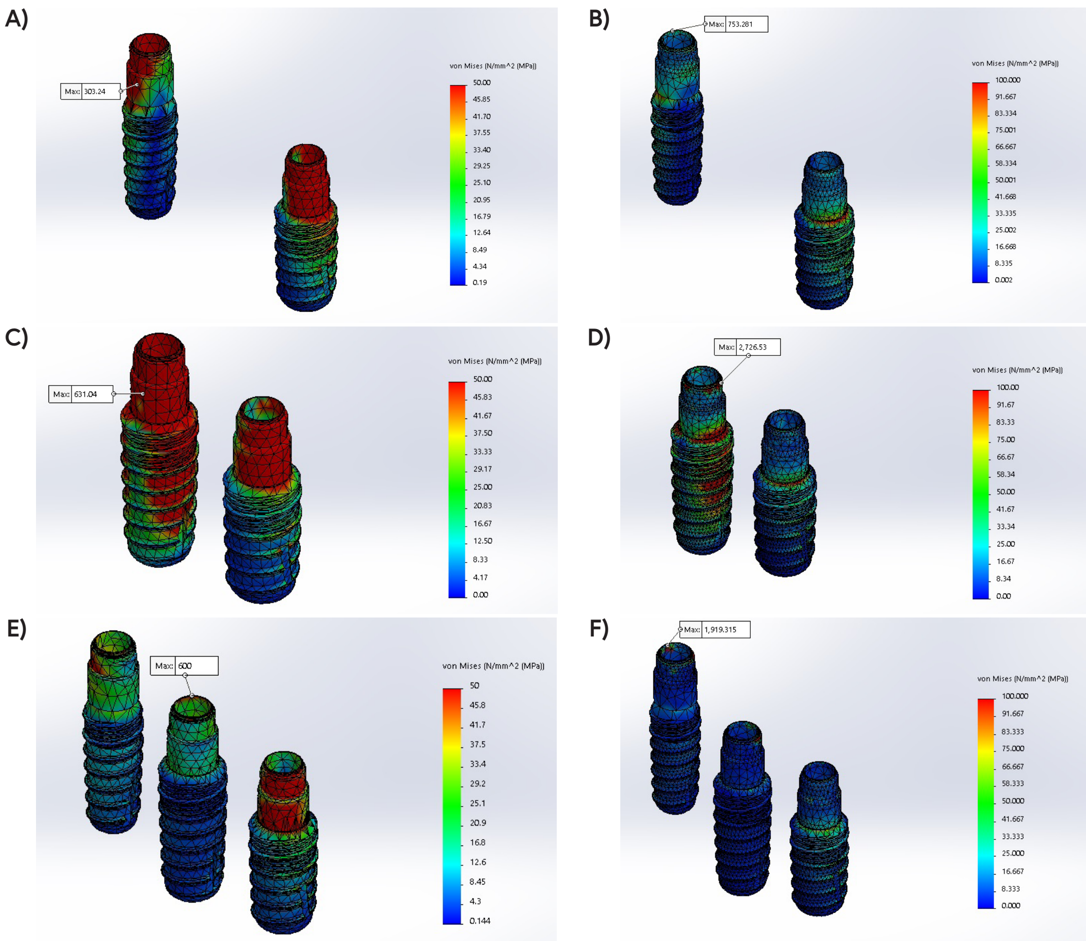

Figure 3 - Stress maps in the implants. (A) ZR bridge; (B) PEEK & ZR bridge; (C) Cantilever ZR bridge; (D) Cantilever PEEK & ZR; (E) separate ZR crowns; (F) Separate PEEK & ZR crowns.

The maximum stress located in the restoration is presented in Figure 4. Stresses were concentrated around the cantilever restorations. Higher stress values were observed in the full zirconia cantilever subgroup, while the combined PEEK & ZR fixed bridge subgroup showed the lowest maximum stress values.

Stress peak descriptive charts were prepared using a qualitative approach, to compare the stress values generated in each model. The combined PEEK & ZR implant restoration showed superior behavior over full ZR implant restoration, as the combined PEEK & ZR implant restoration induced lower stress values in the crown than the full ZR implant restoration, as shown in Table II.

The cantilever design had the highest von Mises stress values compared with the other designs, regardless of the restoration material type. The separate crown designs showed higher von Mises stress values than the fixed bridge design regardless of the restoration material type.

Stress peak charts that compared the maximum von Mises stress generated on the implant level showed that the effect of prosthetic design and material used had the greatest influence. Especially, the implant von Mises stress in full ZR implant restorations were higher than those of the PEEK & ZR models. Furthermore, cantilever design had higher implant values than separate crowns and fixed bridge designs, as shown in Table III.

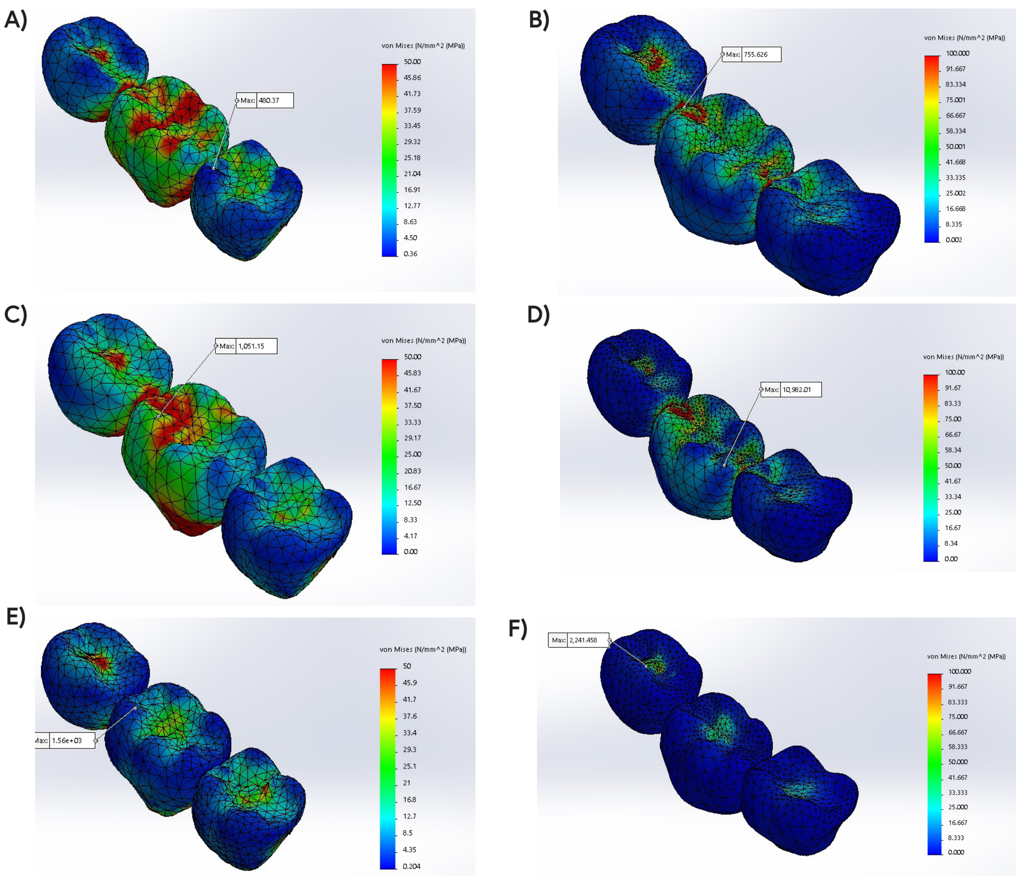

Figure 4 - Stress maps in the restoration. (A) ZR bridge; (B) PEEK & ZR bridge; (C) Cantilever ZR bridge; (D) Cantilever PEEK & ZR; (E) separate ZR crowns; (F) Separate PEEK & ZR crowns.

Table II - Von-Mises stress (MPa) peak descriptive table generated in the restorations for each model

Location	von-Mises stress (MPa) peak in the restorations for each model.					
	Sub group A (ZR)			Sub group B (PEEK & ZR)		
	Fixed fixed (FB)	cantilevr (CB)	Separate crowns (SC)	Fixed fixed (FB)	cantilever (CB)	Separate crowns (SC)
5C	272.091	581.21	324.1	200.83	413.93	256
6C	755.626	1098	607.23	189.86	625.57	254
7C	551	670.19	459.696	182.97	496.64	245

Table III - Von-Mises stress (MPa) peak descriptive table generated in the implants for each model

Location	von-Mises stress (MPa) peak in the implants for each model.					
	Sub group A (ZR)			Sub group B (PEEK & ZR)		
	Fixed fixed (FB)	cantilevr (CB)	Separate crowns (SC)	Fixed fixed (FB)	cantilever (CB)	Separate crowns (SC)
5I	753.281	-	1519.32	303.24	-	254
6I	-	2720.53	1418.97	-	731.04	450
7I	610.8	1780.01	1247.56	250.34	450.84	349

DISCUSSION

This study was conducted to determine whether different implant prosthetic designs and restorative materials had biomechanical effects at the implant, restoration, and bone levels. The null hypothesis of our study was rejected as different implants prosthetic designs and implant prosthetic materials have shown significance impact on the biomechanical behavior at implant, restoration and bone level .

Mechanical complications associated with dissipation of the excessive loads transmitted to the peri-implant bone should be avoided for positive long-term results. The stress or energy transfer between the implant and peripheral bone is affected by essential biomechanical factors, such as the direction of loading and number of implants, prosthetic designs, and material characteristics of the implant or restorative crown. These items are of paramount significance [15].

High stress affects implant prosthesis components by inducing deformation, defined as strain in the peri-implant bone area. Furthermore, implant failure could result from elevated stress and strain levels [16].

Several techniques, including mathematical calculations, photoelastic analysis, and finite element stress analysis, have been used to assess the biomechanical behavior of various implant prosthetic designs and materials. Each technique has its own set of advantages and disadvantages and all methodologies are capable to elucidate the mechanical behavior of implant-system. However, the combination of two or more methods gives more detailed explanation and avoids limitations of a single methodology [17].

In the present study, was used finite element analysis to determine the stress concentration of different implant prosthetic designs and materials. Other methods, such as photoelastic stress analysis and strain gauge analysis, have been used in other studies to assess the biomechanical behavior of various implant prosthetic designs and materials. Each technique has its own advantages and disadvantages, with finite element stress analysis and strain gauge analysis being the most commonly used.

Implant and prosthesis designs capable of promote a certain stability under masticatory loads are a significant aspect of the long-term predictability of implant treatments. However, because of the complicated design of implants and their interactions with the supporting tissues and prosthetic restoration, there is no clinical method to determine the impact of external loading on internal stresses and displacements. The finite-element technique (FEM) was developed for these types of analyses.

The results of the finite element analysis (FEA) were in agreement and consistent with the *in vitro* strain gauge study results and resembled the finding of Wang et al.'s [18] study. The investigators evaluated finite element verification within *in vitro* electronic strain measurements of fixed partial dentures. Their evaluation considered the distribution of stress, which is dependent on the material qualities and geometric configuration of the structure and is a significant component for clinical applications. Using the FEA approach as an appropriate tool for calculating stresses in a loaded structure, with a precise prediction of *in vitro* strain measurement, the FEA model was validated showing strains patterns that were similar to those measured *in vitro*. Thus, they confirmed that a FEA model can be applied to evaluate the load capacity of the fixed dental prosthesis.

Individualized models can be created to account the structural complexity of implant-prosthesis restorations. To simulate the mechanical behavior of dental implants, the present investigation used digital images of the jawbone and a precise 3D geometric model of the bone, superstructure and implants.

The models that have been used a monolithic ZR & PEEK framework to restore posterior edentulous areas was created according to a previous study. Both Zr veneered and Bio HPP crowns revealed successful clinical performance from the clinical performance aspect and patient satisfaction [19]. The present study evaluated the benefit of adding a stress-breaking framework to the implant prosthetic complex and its effect on the overall biomechanical behavior.

The FEA results showed that the cantilever design had the highest von Mises stress values compared to the other designs, regardless of the restoration material type. Separate crown designs showed higher von Mises stress values than fixed bridge designs, regardless of the restoration material type. This finding was in agreement with previous study that used three-dimensional FEA to investigate different implant inclinations and cantilever lengths in the All-on-4 treatment concept. Notably, the investigators discovered that decreasing cantilever length resulted in lower stress values in the peri-implant bone, abutment, and prosthesis [20].

In terms of von Mises stress values in implants, full zirconia implant restoration exhibited greater von Mises stress values than PEEK & ZR implant restoration. This finding by far was the most relevant to the study of Datte et al. [13], who examined the impact of several restorative materials on stress distribution in dental implants. The investigators found that, depending on the crown material, an increase in the elastic modulus reduced the von Mises stress concentration in implants.

The present results are consistent with those from previous FEA that support the hypothesis that internal stress affects the resultant stress distribution. In contrast to the findings of Kaleli et al. [21], who compared the distribution of stress in single implants and peripheral bones in various restorative crowns and customized abutment materials, our results revealed that the stress values of customized zirconia abutments were higher than those of customized PEEK abutments. Changes in the restoration and customized abutment material had no effect on stress distribution in the implant and peripheral bone in all models.

As a limitation of this study to produce more precise prognosis for various clinical situations, additional studies are needed to simulate various implant diameters with different materials. Also, it would be better to include the influence of bone quality.

Another limitation, this investigation evaluated the effect of axial loading only. The direction of loading such as oblique loading may result in different strain generated. Thus, further investigations in deter- mining the strain transfer under angled loading at the implant-abutment connection would contribute to the under- standing of load transfer mechanisms in more complex situations.

The null hypothesis was rejected, and different prosthesis designs can result in different stress outcomes. Furthermore, prosthetic materials affect biomechanical behaviors at the prosthetic component, implant, and bone levels.

CONCLUSIONS

The following conclusions were drawn within the constraints of this study:

Fixed bridge design should be preferable as a favorable prosthetic design when restoring multiple units. The combination of PEEK & ZR can be recommended instead monolithic zirconia bridges to reduce the stress magnitude.

Author's Contributions

MAMA: Worked in Original Draft Preparation, made the Investigations and sample preparation, Resources and Conceptualization of the project idea, finally Writing and Editing under supervision of other coauthors. AMH: Supervision, Project Administration with planning the Methodology of the research then participated in the Review & Editing process with data Resources and Data Curation. GAF: Supervision and Methodology planning with data Review & Editing. AKAE: Supervision and Methodology planning with data Review & Editing of the Original Draft Preparation Then participated in Formal Analysis of the research results and conclusion.

Conflict of Interest

The authors declare no conflict of interest.

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Regulatory Statement

This research was approved by the committee of Faculty of Dentistry Ain Shams University Research Ethics (FDASU-REC).

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