

Biomechanical Evaluation of PEEK Material on Three-Unit Tooth-Implant-Supported Fixed Partial Dentures: A Finite Element Analysis

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Abstract

Polyether ether ketone (PEEK) is a recently introduced polymer reported to exhibit stress-absorbing properties, and it has been evaluated in only a limited number of studies for use in tooth-implant-supported fixed partial dentures (FPDs). This study aimed to evaluate the effect of the prosthetic material on stress accumulation in the teeth, periodontal tissues and implants in tooth-implant-supported FPDs using finite element analysis. It was assumed that the mandibular right first and second molars were missing. Using computed tomography, a three-dimensional scanner and dedicated software, a finite element model of a three-unit tooth-implant-supported FPD was created, in which the implant was placed in the second molar region and the second premolar served as the natural abutment. Five experimental groups were formed (metal-supported ceramic, zirconia-based ceramic, monolithic zirconia, composite-veneered PEEK and monolithic PEEK). A vertical load of 600 N was applied to a food model designed as a negative copy of the pontic occlusal surface, and the maximum von Mises stress values were recorded. Notable differences in von Mises stress values were observed depending on the prosthetic material. Monolithic PEEK, the material with the lowest elastic modulus, produced the highest stress values in the cortical bone (108.94 MPa) and the implant (722.59 MPa), whereas monolithic zirconia exhibited the lowest stress values in the cortical bone, the implant and the tooth. Stress accumulation in dentin was highest in the composite-veneered PEEK group (107.05 MPa). Prosthetic materials can notably affect stress values in tooth-implant-supported FPDs.

Keywords

Biomechanics, Finite element analysis, PEEK, Polyetheretherketone, Stress, Tooth-implant supported fixed partial dentures

Üç Üyeli Diş-İmplant Destekli Sabit Bölümlü Protezlerde PEEK Materyalinin Biyomekanik Değerlendirmesi: Sonlu Elemanlar Analizi

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Özet

Stres emici özellik gösterdiği bildirilen ve yakın zamanda kullanıma giren bir polimer olan polietereeterketon (PEEK), diş-implant destekli sabit bölümlü protezlerde (SBP) sınırlı sayıda çalışmada değerlendirilmiştir. Bu çalışmanın amacı, diş-implant destekli SBP'lerde protetik materyalin diş, periodontal dokular ve implantta oluşan stres birikimi üzerindeki etkisini sonlu elemanlar analizi ile değerlendirmektir. Çalışmada sağ mandibular birinci ve ikinci büyük azı dişlerinin eksik olduğu varsayılmıştır. Bilgisayarlı tomografi, üç boyutlu tarayıcı ve ilgili yazılımlar kullanılarak, implantın ikinci büyük azı bölgesine yerleştirildiği ve ikinci küçük azı dişinin doğal destek olarak kullanıldığı üç üyeli diş-implant destekli bir SBP'nin sonlu elemanlar modeli oluşturulmuştur. Beş deney grubu oluşturulmuştur (metal destekli seramik, zirkonya altyapılı seramik, monolitik zirkonya, kompozit ile veneerlenmiş PEEK ve monolitik PEEK). Gövdenin okluzal yüzeyinin negatif kopyası olarak modellenen besin modeline 600 N'luk dikey kuvvet uygulanmış ve maksimum von Mises stres değerleri kaydedilmiştir. Protetik materyale bağlı olarak von Mises stres değerlerinde belirgin farklılıklar gözlenmiştir. Elastisite modülü en düşük materyal olan monolitik PEEK, kortikal kemikte (108,94 MPa) ve implantta (722,59 MPa) en yüksek stres değerlerini oluştururken; monolitik zirkonya kortikal kemikte, implantta ve dişte en düşük stres değerlerini göstermiştir. Dentindeki stres birikimi en yüksek kompozit ile veneerlenmiş PEEK grubunda (107,05 MPa) bulunmuştur. Protetik materyaller diş-implant destekli SBP'lerde stres değerlerini belirgin şekilde etkileyebilmektedir.

Anahtar kelimeler

Biyomekanik, Sonlu elemanlar analizi, PEEK, Polietereeterketon, Stres, Diş-implant destekli sabit bölümlü protez

1. INTRODUCTION

Despite variances in biomechanical characteristics between natural teeth and implants, the tooth-implant connection remains a viable treatment avenue, often chosen in cases where anatomical constraints or financial considerations come into play [1,2]. Tooth-implant-supported fixed partial dentures (FPDs) are not routinely used in partially edentulous patients. The occasional use of such dentures mainly results from biomechanical considerations [3]. Here, the primary concern is related to the difference between the mobility of the teeth and the behavior of the osseointegrated implant under occlusal forces [4]. This mobility difference between the teeth and the dental implant may cause peri-implant bone loss in tooth-implant-supported FPDs [5,6].

The indications and biomechanical complications of these dentures are highly controversial [7-9]. Long-term clinical studies and systematic reviews have shown low failure rates for tooth-implant-supported FPDs over ten years of follow-up, with high survival rates reported during the first five years [6,10]. A high level of patient satisfaction has been reported with tooth-implant-supported FPDs [11]. In addition, there are studies suggesting that connecting a tooth to an implant represents a viable and alternative option for the fabrication of an FPD for the patient [12].

Previous experimental biomechanical studies on the tooth-implant connection examined the effects of the number of splinted teeth, different occlusal loads and connector types, connector position, bone type, and type of abutment connection on prosthetic components and surrounding tissues [4,13,14].

Finite element analysis (FEA) is a valid method for the assessment of the mechanical behavior of materials in the oral cavity [15]. FEA enables visualization of superimposed structures without changing the physical characteristics of the material. In implantology, FEA has been used to investigate the stress patterns in implant components as well as in the bone around the implant [16]. For these reasons, FEA was chosen for this study.

Previous research has not adequately explored the impact of various prosthetic materials on stress dispersion within the teeth, implants, and adjacent tissues in FPDs supported by a combination of natural teeth and implants. In particular, to the best of our knowledge, no previous finite element study has simultaneously compared five different prosthetic materials — including both monolithic PEEK and composite-veneered PEEK — within the same tooth-implant-supported FPD model. This design allows a direct comparison of recently introduced low-modulus polymer materials with conventional metal-ceramic and zirconia-based restorations under identical geometry, loading, and boundary conditions. Therefore, this study aimed to comparatively evaluate stress distribution in the tooth, bone, implant, and periodontal ligament (PDL) across different prosthetic materials using three-dimensional (3D) finite element analysis. The null hypothesis was that utilizing PEEK, a prosthetic material characterized by a low elastic modulus, would result in reduced stress accumulation across all models.

2. MATERIAL AND METHOD

2.1. Model Design

This study was approved by the Non-Interventional Research Ethics Committee of Firat University (session date: 26.01.2023, session number: 2023/02-05). For study purposes, it was presumed that the right mandibular first and second molars were missing. A finite element model of a three-unit tooth-implant-supported FPD was constructed in which the implant was placed in the edentulous area of the right mandibular second molar and the second premolar tooth was used as the natural abutment. A mandibular model derived from a computed tomography (CT) scan was used. The tooth model was digitized by scanning a natural mandibular second premolar tooth with a micro-CT device (SkyScan 1174v2; Bruker micro-CT, Kontich, Belgium) at 100 kV, 100 μ A, 180° around the vertical axis, with a camera exposure time of 1650 ms, a rotation step of 0.4°, and an average frame of 2, using a 0.5 mm thick aluminum filter. A bone-level dental implant (4.1 $\times$ 10 mm), abutment, and screw were used as the implant system (Straumann AG, Basel, Switzerland). The tooth, implant, abutment, and screw were scanned in 3D with an Activity 880 laser scanner (smart optics Sensortechnik GmbH, Bochum, Germany). After scanning, Rhinoceros 4.0 (McNeel, Seattle, WA, USA) 3D modeling software, VRMesh Studio (Virtual Grid Inc., WA, USA), and Algor Fempro (ALGOR, Inc., Pittsburgh, PA, USA) software were used. Type 2 trabecular bone surrounded by 2 mm of cortical bone was modeled, with an assigned mucosa thickness of 1 mm.

In metal-supported ceramic restorations, ideally, the metal thickness should be at least 0.5 mm, and the ceramic layer should be a maximum of 2 mm thick [17]. The anatomic form of the denture was modeled in accordance with the geometry described in Wheeler's Dental Anatomy, Physiology, and Occlusion textbook [18]. A three-unit tooth-implant-supported FPD model and 3D images of all the models were obtained, as shown in Figure 1a and Figure 1b. A cement thickness of 0.1 mm was modeled between the prosthesis and the abutment. The coefficient of friction at all contact surfaces was set at 0.5. The materials used for all models were assumed to be homogeneous, isotropic, and linearly elastic. Before the analysis, the abutment and screw were placed in the implant by applying 35 Ncm torque. In addition, it was assumed that the implant and bone were perfectly bonded at the contact area.

The elastic modulus and Poisson's ratio of all the materials modeled are shown in Table 1. In this study, five experimental groups were created, as outlined in Table 2.

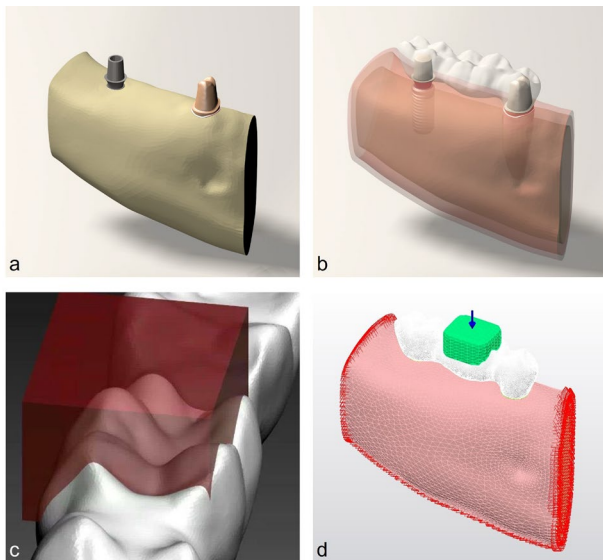


Figure 1. (a) Three-unit tooth-implant-supported fixed partial denture model, with the mandibular right second premolar as the natural abutment tooth, the first molar as the pontic, and the implant placed in the second molar region; (b) three-dimensional images of the assembled models for all experimental groups; (c) positioning of the food model, created as a negative imprint of the pontic occlusal surface, on the FPD model; (d) application of the 600 N vertical load to the meshed finite element model.

Table 1. Elastic modulus and Poisson's ratio of all materials tested.

	Young Modulus (GPa)	Poisson's Ratio	References
Cortical bone	13.7	0.30	[21]
Trabecular bone	1.37	0.30	[22]
Ceramic	69	0.30	[23]
Metal framework (Ni-Cr)	200	0.33	[21]
Titanium	110	0.30	[24]
Monolithic zirconia	210	0.30	[24]
PEEK	3.5	0.36	Values provided by the manufacturer (JUVORA Dental Disc)
Indirect resin composite	50	0.30	[25]
Dentin	18.6	0.31	[26]
PDL	0.0689	0.45	[26]
Resin cement	7	0.30	[22]
Mucosa	0.001	0.37	[26]
Food (apple)	0.0034	0.10	[27]

Table 2. Experimental groups.

Groups	Restoration Types
Group MP	Metal-supported ceramic
Group ZP	Zirconia-based ceramic
Group Z	Monolithic zirconia
Group PC	PEEK framework veneered with resin composite
Group P	Monolithic PEEK

The models were imported into the ALGOR software (ALGOR, Inc., PA, USA) for conversion into STL files for FEA. In order to perform FEA in the ALGOR software, the models needed to be meshed completely. The models were meshed with four- to eight-node brick elements, using eight-node elements as much as possible. In this study, the maximum possible numbers of elements and nodes were used in order to obtain more realistic results. The meshes of Groups MP, ZP, and PC contained 162,627 nodes and 818,851 elements, whereas those of Groups Z and P contained 109,484 nodes and 505,949

elements; the higher node and element counts in Groups MP, ZP, and PC reflect the additional veneering layer modeled in these groups. A fixed boundary condition was applied to restrict the external surface elements of the cortical bone in all degrees of freedom.

2.2. Stress Analysis

A static vertical (occluso-apical) load of 600 N was applied to the food model, which was positioned on the occlusal surface of the pontic and modeled as a negative imprint of the pontic occlusal surface (Figure 1c and Figure 1d). This approach allowed the load to be distributed over the entire functional occlusal surface rather than at arbitrary point contacts, thereby simulating a more physiological loading condition. A load magnitude of 600 N was selected to represent the maximum voluntary bite force reported for the posterior region [19]. After the analysis, maximal von Mises (equivalent) stress values were derived for various components, including the peri-implant cortical bone, trabecular bone, implant, tooth, periodontal ligament (PDL), implant abutment, abutment cement, tooth cement, and crown. Von Mises stress provides information about the point where the elastic boundary is exceeded. A color scale was used to allow for comparisons among the experimental groups. All stress values were recorded in MPa. In addition, the results of the stress analysis for all groups were transformed into graphs to facilitate the interpretation of the findings.

3. RESULTS

The results of the von Mises stress analysis are presented in Figure 2 and Table 3. The data showed that the use of different prosthetic materials was associated with notable changes in von Mises stress values in all models except the PDL and trabecular bone.

Table 3. Comparison of von Mises stress values (MPa) among the groups.

Structures	Group MP	Group ZP	Group Z	Group PC	Group P
Cortical bone	87.18	87.19	81.35	95.52	108.94
Trabecular bone	19.02	19.02	19.02	19.00	18.93
Implant	566.94	567.01	525.68	629.25	722.59
Dentin	54.62	54.66	41.89	107.05	52.95
Abutment screw	681.53	681.53	681.32	680.96	680.73
PDL	7.55	7.55	7.49	7.73	7.73
Implant abutment	179.11	179.14	157.4	202.48	240.72
Abutment cement	92.80	92.72	73.90	235.34	195.16
Tooth cement	53.018	53.04	35.73	139.80	54.40
Crown-veneer	238.29	238.32	239.99	558.29	94.02
Framework	357.42	354.69	∅	73.10	∅

3.1. Stresses in the Bone

Across all groups, von Mises stress predominantly localized in the cortical bone and around the neck of the implant. Most of the load transferred from the implant to the bone was absorbed by the cortical bone; therefore, the trabecular bone was exposed to less stress. In all groups, von Mises stress values for the trabecular bone were

similar, showing no notable differences. Von Mises stress values for the cortical bone showed substantial differences among the prosthetic materials. The highest stress value in the cortical bone was observed in Group P (108.94 MPa), representing the prosthetic material with the lowest elastic modulus (PEEK). In contrast, the prosthetic material with the highest elastic modulus (Group Z; zirconia) exhibited the lowest stress value (81.35 MPa).

3.2. Stresses in the Implant

In all groups, the stress was concentrated around the implant neck. The stress in the implants was markedly affected by the type of prosthetic material tested. Stress values were highest in Group P (722.59 MPa) and lowest in Group Z (525.68 MPa).

3.3. Stresses in the Dentin and the Periodontal Ligament

In all groups, stresses in the teeth were concentrated in the mesiobuccal aspect of the cervical region. Stress in the teeth was markedly affected by the type of prosthetic material. While the highest stress values in the teeth were observed in Group PC (107.05 MPa; PEEK framework veneered with resin composite), Group Z showed the lowest stress values (41.89 MPa).

In the PDL, stress concentration was observed in the mesial aspect of the cervical region in all groups. The type of prosthetic material did not have a notable impact on stress in the PDL.

3.4. Stresses in the Implant Abutment and the Abutment Screw

In all groups, maximal stresses in the abutment screws were found in the apical aspect of the screws. Stress on the screws did not change notably with the use of different prosthetic materials.

All groups exhibited stress concentration around the abutment neck. Marked differences were observed among the prosthetic materials in terms of stress in the abutments. The analysis revealed that the highest stress in the abutments was observed in Group P (240.72 MPa), whereas the lowest was recorded in Group Z (157.4 MPa).

3.5. Stresses in the Cement Layers

In the cement model, stresses in the abutment cement were concentrated in the mesial aspect of the cervical region in all groups. Stress in the cement varied substantially depending on the prosthetic material used. In the abutment cement, the highest stress accumulation was observed in Group PC (235.34 MPa) and the lowest in Group Z (73.9 MPa).

In the tooth cement model, stresses were concentrated in the distal aspect of the cervical region. Stresses in the tooth cement were markedly affected by the type of prosthetic material used. While Group PC displayed the highest stress in the tooth cement (139.8 MPa), Group Z showed the lowest stress (35.73 MPa).

3.6. Stresses in the Prosthetic Materials

Stresses in the crown were concentrated in the mesial collar region of the right mandibular second molar. Stresses occurring in the crown differed notably among the groups. Stresses measured in the crown were highest in Group PC (558.29 MPa) and lowest in Group P (94.02 MPa). Stress in the frameworks was lowest in Group PC (73.1 MPa).

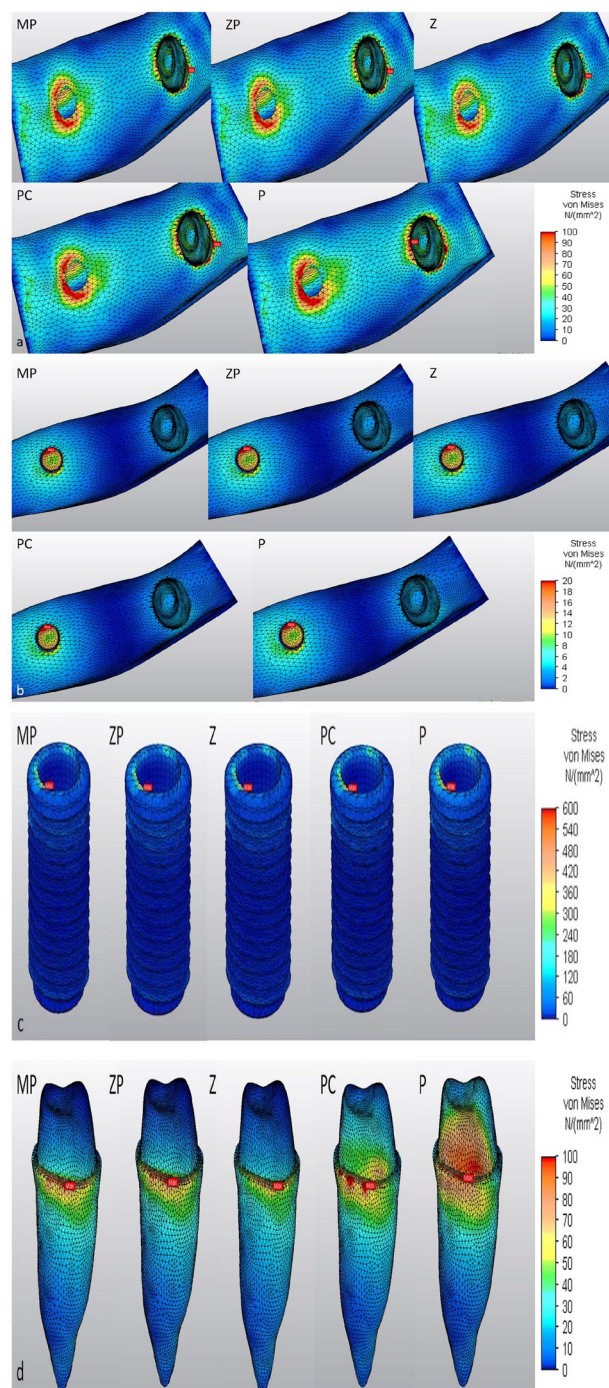


Figure 2. The maximum von Mises stress values (MPa) and stress distributions in all groups: (a) cortical bone; (b) trabecular bone; (c) implant; (d) dentin; (e) abutment screw; (f) PDL; (g) implant abutment; (h) abutment (crown) cement; (i) tooth cement; (j) framework; (k) crown/veneer.

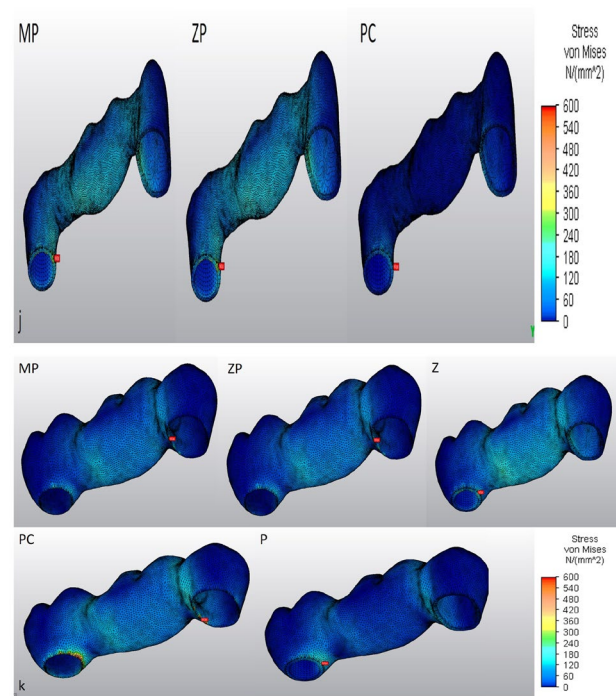
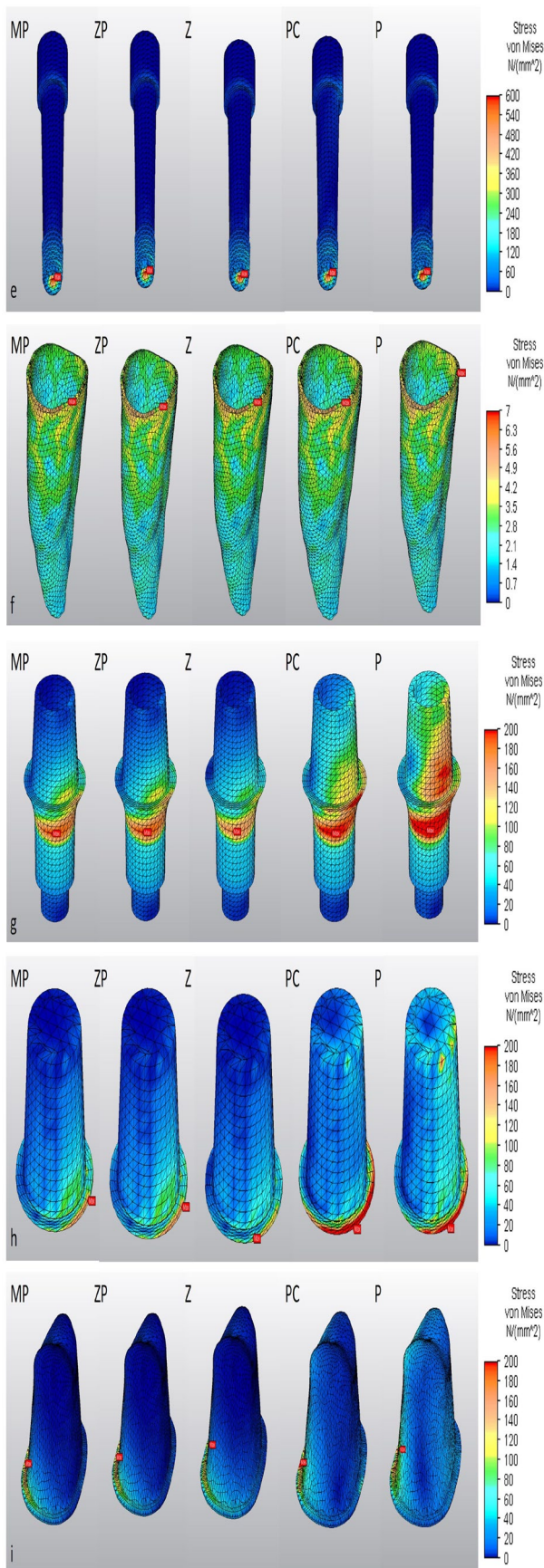


Figure 2 Cont. The maximum von Mises stress values (MPa) and stress distributions in all groups: (a) cortical bone; (b) trabecular bone; (c) implant; (d) dentin; (e) abutment screw; (f) PDL; (g) implant abutment; (h) abutment (crown) cement; (i) tooth cement; (j) framework; (k) crown/veneer.

4. DISCUSSION AND CONCLUSION

In this FEA study, stress analyses were performed to evaluate changes in stress levels using different prosthetic materials in tooth-implant-supported FPDs. The null hypothesis of the study posited that the utilization of PEEK, a prosthetic material characterized by a low elastic modulus, would result in reduced stress accumulation across all models. Since the results of this study showed notable variations in stress values depending on the prosthetic material used, the null hypothesis was rejected. When the results are considered together, monolithic zirconia (Group Z) consistently produced the lowest stress values in the cortical bone (81.35 MPa), implant (525.68 MPa), dentin (41.89 MPa), implant abutment (157.4 MPa), and both cement layers. In contrast, monolithic PEEK (Group P) produced the highest stresses in the cortical bone (108.94 MPa), implant (722.59 MPa), and implant abutment (240.72 MPa), whereas composite-veneered PEEK (Group PC) generated the highest stresses in the dentin (107.05 MPa), abutment cement (235.34 MPa), tooth cement (139.80 MPa), and crown veneer (558.29 MPa). The metal-ceramic (Group MP) and zirconia-based ceramic (Group ZP) groups showed nearly identical, intermediate stress values. Stresses in the trabecular bone, PDL, and abutment screw were essentially unaffected by the prosthetic material.

In an article by Gotfredsen et al. discussing the consensus and recommendations on several issues concerning implants, in response to the question “Should we perform tooth extraction in the mandibular premolar region in order to make FPDs?”, it was argued that the tooth-implant connection can be performed without tooth extraction but biomechanical risks should be considered [7]. In our study, to minimize complications in patients for

whom tooth-implant FPDs are planned, we compared stress levels among various framework prosthetic materials.

A study conducted by Nickenig et al., examining the occurrence of biological and technological complications in tooth-implant-supported FPDs over an almost 5-year follow-up period, proposed that employing rigid functional connections could yield outcomes comparable to those of solely implant-supported FPDs [8].

Lin et al. explored the biomechanical interactions in tooth-implant-supported FPDs using different types of connectors (rigid and non-rigid) under several loading conditions. They suggested that employing a non-rigid connector might offer better efficacy in compensating for the disparate mobility between natural teeth and implants when subjected to axial loading forces [20].

In a study by Koosha et al., stresses accumulated around the natural teeth and the implant in tooth-implant-supported FPDs were investigated under occlusal forces using 3D finite element analysis. They observed maximum stress values at the crestal bone of the implant, and found that tooth mobility was more pronounced than implant mobility in all models [9]. Similarly, in our study, there was greater stress accumulation in the implant than in the tooth in all models, and the cortical bone absorbed most of the loads transferred by the implant to the bone, resulting in less stress concentration in the trabecular bone. This may cause bone resorption around the implant. Tsouknidas et al. examined whether bone quality has an impact on the biomechanical behavior of a tooth in tooth-implant-supported FPDs using a rigid or non-rigid attachment. For the implant-trabecular bone interface, the fastening screw, and the implant neck, the highest stress accumulation was observed in Type 3 bone when a rigid connection was used. The lowest stress values were found for the implant-trabecular bone interface, the implant neck, and the connector in Type 1 bone with the use of a rigid connection [13]. Similarly, in our study, the highest stress value in the peri-implant bone was observed in Group P, in which the prosthetic material with the lowest elastic modulus (PEEK) was used, whereas Group Z (the prosthetic material with the highest elastic modulus) showed the lowest stress accumulation in the bone.

In all models tested in our study, stress was concentrated in the mesial surface of the implant and the distal surface of the tooth. In general, greater stress accumulation in the implant was observed in the cross-sectional configuration of all models. This is related to first-class lever biomechanics, which is in line with previous reports [21,22].

Wang et al. conducted a study investigating the biomechanical responses of endodontically treated tooth-implant-supported dentures. They explored these responses by varying the implant system and load type through finite element analysis. The authors noted that, when connected to a tooth restored with a post-core and crown, one-piece implants without eccentric occlusal contacts exhibited superior mechanical responses compared to two- or three-piece implants [23].

Al-Omiri et al. conducted a review of studies on tooth-implant combinations and presented their views. They suggested that, even though there is a higher need for repair and maintenance for tooth-implant FPDs compared

to free-standing implants, in suitable cases they may be considered a viable alternative for the rehabilitation of partial edentulism if they make the treatment less complex, more cost-effective, and more acceptable for the patient. It was also stated that the use of a rigid connection and permanent cementation are associated with a lower likelihood of complications [24]. Keeping these considerations in mind, in our study, we sought to determine the best prosthetic material for the long-term use of tooth-implant-supported dentures.

Chen et al. conducted a study to examine the biomechanical behavior of the abutment teeth in patients treated with tooth-implant-supported overdentures with telescopic crowns. They reported that tooth-implant-supported telescopic crown dentures were able to protect the natural teeth and periodontal support tissues, and suggested that they might be regarded as a valuable treatment option for edentulous patients [25]. In light of the aforementioned data and our findings, tooth-implant-supported FPDs can be considered a suitable treatment option for partially edentulous patients.

In a study by de Paula et al. comparing the biomechanical behavior of tooth-implant-supported dentures by changing the design of the implants (external hexagon/Model EH; internal hexagon/Model IH), the biological risk for bone was similar with both dentures. Restorations with IH implants were found to be associated with a lower risk of biomechanical failure [26]. In our study, we observed that the prosthetic material used markedly changed the stress distribution in the bone and implant. Prosthetic materials with a lower elastic modulus were associated with greater stress in the bone. This presents a high risk of biomechanical failure by causing bone loss.

Borg et al. reviewed the relevant literature for possible complications and the overall survival of tooth-implant-supported FPDs. They suggested that tooth-implant-supported dentures rigidly cemented to periodontally healthy teeth represent a good treatment option for non-smoking individuals with good oral hygiene [27]. In future studies, successful long-term outcomes can be achieved with tooth-implant-supported dentures using the most suitable prosthetic materials for the correct indication.

Sirandoni et al. assessed the biomechanical behavior of different framework materials in implant-supported mandibular FPDs using FEA. Among the materials, frameworks with titanium, cobalt-chromium, and zirconia were found to exhibit more favorable outcomes from a biomechanical perspective [28]. Likewise, our study found that the monolithic zirconia models exhibited the lowest stress values for both teeth and implants. Additionally, employing a framework material with a low elastic modulus led to a notable increase in stress levels.

A study was conducted by Arinc to evaluate the stress caused by the prosthetic material in the trabecular and cortical bones, framework, and implants using FEA. In that study, zirconia-reinforced PMMA (polymethyl methacrylate) exhibited increased stress values in the implants and bone tissue and the lowest stress values in the framework. The author concluded that prosthetic materials may affect stress values [29]. In our study, the lowest stress values were observed in the cortical bone,

implant, and tooth in the monolithic zirconia models, while the highest stress values in the cortical bone and implant were found for the monolithic PEEK models.

The higher stresses observed around the implant and in the peri-implant cortical bone with the PEEK models can be explained by basic load-transfer mechanics. The distribution of an occlusal load within a fixed prosthesis depends on the relative stiffness of the restorative material and the supporting structures. A rigid, high-modulus framework such as monolithic zirconia deforms minimally under load and distributes the applied force over a wider area of the prosthesis before transferring it to the abutments; consequently, the peak stresses reaching the implant, the abutment, and the crestal cortical bone are reduced. In contrast, a low-modulus framework such as PEEK undergoes greater elastic deformation under the same load, and this deflection concentrates the transferred load on the stiffer components of the system — the titanium implant and the surrounding cortical bone — rather than dissipating it within the prosthesis, thereby increasing the local stress peaks at the implant neck and the crestal bone region. Recent finite element analyses comparing polymeric and ceramic frameworks in implant-supported prostheses have likewise shown that framework stiffness markedly influences the magnitude and location of the stresses transferred to the implant components and the supporting bone [30,31]. Therefore, the frequently cited “stress-absorbing” capacity of PEEK, which is mainly related to its damping behavior under dynamic or impact loading, should not be interpreted as a reduction of the static load ultimately transferred to the supporting implant and bone.

Beyond the numerical stress values, the present findings have clinical implications for material selection in tooth-implant-supported FPDs. Monolithic zirconia combines a high elastic modulus with high flexural strength and fracture toughness [32], and, as reflected in the present models, it transmitted the occlusal load with lower stress concentrations in the peri-implant cortical bone, dentin, implant abutment, and cement layers. Clinically, zirconia-based and metal-ceramic multiple-unit FPDs have shown favorable survival rates [33], although antagonist enamel wear and low-temperature aging of zirconia remain points of attention [32]. Conversely, PEEK offers a low specific weight, good biocompatibility, intraoral repairability, and an elastic modulus closer to that of bone, which has been suggested to provide a shock-absorbing effect [34]. However, in the present study, this low stiffness shifted the load toward the implant, the abutment, and the peri-implant cortical bone, which may increase the risk of marginal bone loss under long-term functional loading. Furthermore, PEEK frameworks require composite veneering for acceptable esthetics, and the veneer and adhesive interfaces represent potential weak links, as reflected by the high stresses observed in the veneer and cement layers of Group PC and by reports on the bonding and fracture behavior of veneered PEEK restorations [35]. Therefore, although PEEK may be considered in selected clinical situations, monolithic zirconia appears to be biomechanically more favorable for tooth-implant-supported FPDs until long-term clinical evidence for PEEK becomes available.

The limitations of this study are acknowledged. Despite the high reliability of finite element stress analysis in dentistry, this method can only partially simulate biological structures and intraoral conditions. All materials, including bone and the periodontal ligament, were assumed to be homogeneous, isotropic, and linearly elastic. However, cortical and trabecular bone exhibit anisotropic behavior, and the periodontal ligament shows nonlinear, viscoelastic characteristics and was modeled here as a simplified linear elastic layer. In addition, complete osseointegration was assumed, with the implant and bone perfectly bonded at the interface, which does not fully reflect clinical bone-implant contact ratios. These simplifications may influence the quantitative stress values; therefore, the results of this study should be interpreted comparatively rather than as absolute values. Moreover, masticatory forces are generally multidirectional and cyclic in nature, whereas a single static vertical load was applied in the present study, and fatigue behavior and thermal cycling were not evaluated. Furthermore, a formal mesh convergence analysis was not performed; however, high mesh densities (up to 162,627 nodes and 818,851 elements) were used to increase the accuracy of the results. Future studies incorporating oblique and dynamic loading conditions, fatigue analysis, and anisotropic material models may provide more clinically relevant information.

Within the limitations of this finite element analysis, variations in stress values were observed depending on the prosthetic material used in tooth-implant-supported FPDs, whereas von Mises stresses in the trabecular bone, abutment screw, and PDL were essentially unaffected. Under the tested conditions, framework materials with a higher elastic modulus provided a more favorable stress distribution: the monolithic zirconia model exhibited the lowest stress values in the cortical bone, implant, dentin, implant abutment, and cement layers. In contrast, the use of a low-elastic-modulus material such as PEEK concentrated stresses in the peri-implant cortical bone and the implant, which may predispose to early marginal bone loss and, eventually, implant failure. Therefore, the use of a framework material with a high elastic modulus may improve the long-term survival of tooth-implant-supported FPDs.

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