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Finite Element Stress Analysis of PEEK, Glass Fiber and Zirconia Post-Core Systems in Maxillary Central Incisor

Maksiller Santral Dişte PEEK, Cam Fiber ve Zirkonya Post-Kor Sistemlerinin Sonlu Elemanlar Stres Analizi

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ÖZET

Amaç: Bu çalışmada maksiller santral kesici diş köklerinde kullanılan üç farklı post-kor sisteminin (polieter eter keton (PEEK), cam fiber ve zirkonya) yapısal gerilme dağılımlarının sonlu eleman analizi (SEA) ile incelenmesi amaçlanmıştır.
Materyal ve Metot: Çalışmada, SEA için hazırlanan maksiller santral kesici dişin ana geometrisi intraoral tarayıcı kullanılarak elde edilmiştir. Dişe ait diğer bileşenler, literatürden elde edilen veriler temelinde bilgisayar destekli parametrik bir tasarım yazılımı kullanılarak modellenmiştir. Post materyali olarak cam fiber, PEEK ve zirkonya ele alınmıştır. Kronlanmış olarak modellenen dişin palatal yüzeyine 45° açı ile 100 N kuvvet uygulanmış, analizler neticesinde, modeller üzerinde ortaya çıkan eşdeğer gerilme (Von Mises) dağılımları ve deformasyon davranışına ait görseller ve sayısal değerler karşılaştırılarak değerlendirilmiştir.
Bulgular: Tüm analizler neticesinde en yüksek eşdeğer gerilme değeri 32.76 MPa olarak PEEK post-korda görülmüştür. Cam fiber ve zirkonya postlar için gerilme değerleri sırasıyla 0.80 MPa ve 21.17 MPa elde edilmiştir. Köklerdeki maksimum eşdeğer gerilme değerleri karşılaştırıldığında zirkonya ve PEEK postlu modellerde sırasıyla 69.01 MPa ve 58.22 MPa cam fiber postlu modelde ise 72.79 MPa bulunmuştur.
Sonuç: PEEK post-kor modellenen kökteki gerilme değerinin büyüklüğü, cam fiber post ve zirkonya post modellenen köklerden daha düşük elde edilmiştir. Bu durum, klinik pratikte diş çekimi gerektiren komplikasyonları azaltabilir olduğunun göstergesi olarak yorumlanabilir ancak bu konuda ileriki klinik araştırmaların yapılması faydalı olacaktır.

Anahtar Kelimeler: Polieter eter keton, Cam fiber, Zirkonya, post-kor, Sonlu elemanlar analizi.

ABSTRACT

Objective: This study aims to analyze structural strength features (such as deformation and stress distributions) of polyether ether ketone (PEEK), glass fiber and zirconia post-core systems utilized in maxillary central incisor roots by means of finite element analysis (FEA).
Material and Method: The main geometry of maxillary central incisor considered in this study was obtained using an intraoral scanner. Other sub-components were modelled in a parametric computer aided design software based on the data obtained from the literature. Glass fiber, PEEK and zirconia were defined as post materials. 100 N force was applied with 45° angle on the palatal surface of veneered tooth in the FEA set up. The FEA was solved with linear material model and static linear loading assumptions through a commercial FEA code. Visuals and numerical results related to equivalent stress (Von Mises) and deformation distributions were interpreted.
Results: Maximum equivalent stress value of 32.76 MPa was calculated at the PEEK post-core. The maximum values for glass fiber and zirconia posts were 0.80 MPa and 21.17 MPa, respectively. Maximum equivalent stress values at the tooth roots in the glass fiber, zirconia and PEEK posts were 72.79 MPa, 69.01 MPa and 58.22 MPa respectively.
Conclusion: The stress magnitude experienced at the PEEK post-cores on the root was lower than glass fiber post and zirconia post. Regarding to this, although, it may be concluded that PEEK may reduce the complications that require tooth extraction in clinical practice, further researches are suggested including clinical trials.

Keywords: Polyether ether ketone, Glass fiber, Zirconia, Post-core, Finite element analysis.

INTRODUCTION

Dental post-core systems have been widely applied for the restoration of teeth that have lost a prominent amount of their crown structure due to caries, endodontic treatment, tooth fracture, or previous extensive restorations (Fraga et al., 1998; Akkayan and Gülmez, 2002). The preferred post system should provide adequate retention of the core, impart minimal stress on the tooth, and should allow easy removal to permit endodontic retreatment, if necessary (Ferrari et al., 2000).

Commonly, the post-core systems in use can be divided into two main categories. The first category is one-piece post-core system (cast or CAD-CAM) and the second one is two-pieces system which includes a prefabricated post and composite resin core. Individual post-core systems can be simply adapted to the various shapes of the root canal and have exceptional mechanical strength (Fraga et al., 1998; Martinez-Insua et al., 1998; Akkayan and Gülmez, 2002). One-piece post-core restorations provide the missing structure at the post and core interface (Liu et al., 2010).

Post material is recommended to have mechanical properties similar to dentine (Mannocci et al., 1999; Rosentritt et al., 2000; Schmitter et al., 2006; Faria-e-Silva et al., 2009). As the difference between elastic modulus values of post material and dentine increases, enormous structural stress concentration may arise around the post. This situation may result in catastrophic root fractures (Fraga et al., 1998; Akkayan and Gülmez, 2002; Newman et al., 2003).

Fiber-reinforced posts are widely used due to their ease of use, aesthetic properties and elastic modulus similar to dentine (de Almeida Goncalves et al., 2006). Some studies indicated that the fracture resistance of teeth restored with glass-fiber posts is equal or greater than that of teeth restored with metal posts (Teixeira et al., 2006; Seefeld et al., 2007). While the application of high elastic modulus post-core systems such as zirconia has always been a matter of debate, it has also been shown that glass fiber and zirconia posts have the same fracture resistance (Akkayan and Gülmez, 2002; Stricker and Göhring, 2006). The fracture resistance and fracture mode were similar for prefabricated zirconia, fiber and casting posts (Xible et al., 2006). Some studies suggested that zirconia could even reinforce the tooth structure due to its mechanical properties and offer better stress distribution along the roots (Rosentritt et al., 2000). Also, the authors stated that one-piece zirconia post-core provided greater toughness, maximal adaptability to the canal, and adequate esthetics (Awad and Marghalani, 2007; Streacker and Geissberger, 2007). But especially zirconia posts are not recommended for the posterior region because of the higher occlusal forces and should be avoided in patients with parafunctional habits (Michalakis et al., 2004).

PEEK is a synthetic, whitish color, polymer-based material that has been used in orthopedics for many years. Advantages of PEEK are its similar elasticity to bone, color stability, low weight, low allergenic potential, low plaque accumulation and lack of corrosion (Maekawa et al., 2015; Zoidis and Papathanasiou, 2016; Skirbutis et al., 2018). The elastic modulus of PEEK matching to dentin is a key advantage that reduces forces transferred to the restorations and enables this material to function as a stress breaker, as uniformly distributed stress has been reported when dental materials have an elastic modulus similar to dentin (Kurtz and Devine, 2007; Stawarczyk et al., 2014; Henriques et al., 2018). Having been the subject of many studies, PEEK has recently been preferred in dental implant applications, crown-bridge restorations and removable dentures and its components, dental implants, custom abutments, maxillary obturator prostheses, and orthodontic wires because its physical and mechanical properties are similar to bone and dentine (Uhrenbacher et al., 2014; Maekawa et al., 2015; Skirbutis et al., 2018). This material, which exhibits high-fracture resistance with a fracture load of 1383 N, has become an alternative to glass ceramics and metal with its shock-absorbing ability (Stawarczyk et al., 2013; Stawarczyk et al., 2014; Chaijareenont et al., 2018). PEEK was shown to be an ideal alternative for CAD/CAM restorations and suitable for three-unit fixed partial dentures (Stawarczyk et al., 2015). PEEK is also an attractive dental material for the production of customized post-core systems because of its wide range of production and machinability options, including milling and pressing (Zoidis and Papathanasiou, 2016).

The aim of this study was focusing on the structural stress magnitudes and distributions that occur on the PEEK material as an alternative to the glass fiber post and zirconia post-core utilized in maxillary central incisor roots by means of finite element analysis.

MATERIAL and METHOD

The study was approved by the Akdeniz University Faculty of Medicine Clinical Research Ethics Committee (approval number: 20.07.2016-428). The geometry of the standard-size maxillary central incisor used in the study was obtained using an intraoral scanner (3Shape TRIOS 3, Copenhagen, Denmark) and a software (3Shape, Copenhagen, Denmark). Tissues supporting the teeth and other components were modelled using a software (Design Modeler, Ansys Software, ANSYS Inc., Canonsburg, PA) with the data obtained from the literature review (Picanço et al., 2013).

Two models were used in order to compare three different post-core systems (Figure 1). The first model was two-piece system which includes a prefabricated glass fiber post and composite resin core. When prefabricated glass fiber posts are preferred, composite resin, which is different from glass fiber in terms of mechanical properties, is used in core. For this reason, the first model was prepared in two pieces (Lee et al., 2017). The second was a model representing the zirconia and PEEK post-core systems, in which post and core were integrated. To investigate the effect of the post-core materials solely, rather than the shape effects, the sizes of all post-core systems were designed exactly uniform in the present study.

Following the general recommendation, the post diameter was one fifth of the root thickness and the length of post was set to around three quarters of the root length (Nergiz et al., 2002). The components of model consisted of cortical and trabecular bone, periodontal ligament, tooth root, gutta percha cone, post cement, one-piece or two-piece post-core, ceramic crown and crown cement (Figure 1).

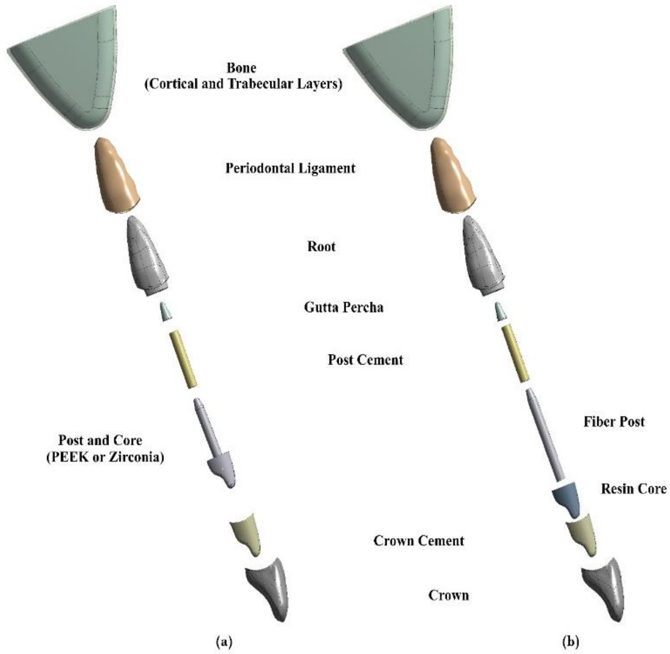

Figure 1. Components of geometric models; (a): Post and core integrated model for simulating PEEK and zirconia post-core system, (b): Model for simulating prefabricated glass fiber post and resin core.

The solid models were transferred to ANSYS 14.5.7 (ANSYS Inc., Canonsburg, PA). All models were meshed using tetrahedral elements as shown in Figure 2 (655058 nodes, 426900 elements). The material model used in the FEA was considered homogeneous, linearly elastic and isotropic. The material properties assigned to the models are shown in Table 1 (Krejci et al., 1994; Saskalauskaite et al., 2008; González - Lluch et al., 2009; Chen et al., 2015). The FEA models were fixed from the cortical and trabecular bone base. The loading was applied on the long axis of the tooth at an angle of 45° from the palatal surface, 2 mm cervical of the incisal edge and 100N. The 100 N load was determined from the current dental literature (Asmussen et al., 2005; Toksavul et al., 2006; Mezzomo et al., 2011). The resulting stresses were calculated as von Mises stresses for all components. Visuals of stress distribution were obtained by scaled the stress-related color distribution in all models. In this method, color distribution is scaled with a certain stress range. Thus, the same stress magnitudes in each model causes formation of the same color. Stress distributions were evaluated through numerical data and deformation visuals obtained from simulation results. All the results were compared and interpreted accordingly.

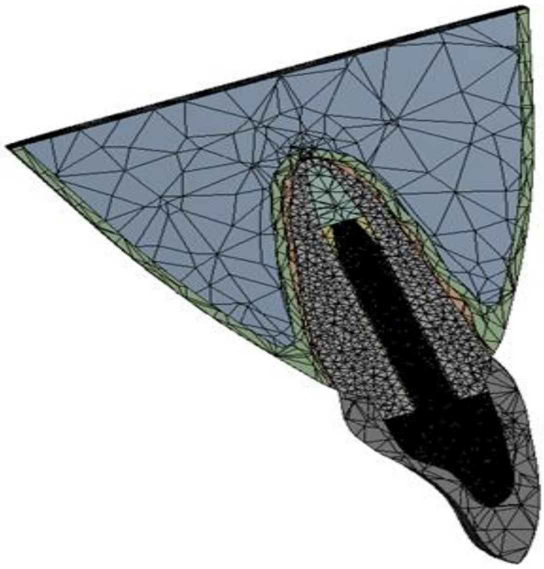

Figure 2. Sagittal sections view of the finite element mesh of post-core restored tooth model.

Table 1. Mechanical properties of materials used in FEA

Materials	Elastic Modulus (GPa)	Poisson Ratio	References
Cortical bone	13.7	0.30	Krejci et al. 1994
Trabecular bone	1.37	0.30	Krejci et al. 1994
Periodontal ligament	0.069	0.45	Krejci et al. 1994
Dentin	18.6	0.31	Krejci et al. 1994
Gutta percha	0.69	0.45	Krejci et al. 1994
Cement (for post)	5	0.30	Krejci et al. 1994
Glass fiber post	20	0.33	González- Lluch et al. 2009
Composite resin (for core)	20	0.30	Krejci et al. 1994
Zirconium oxide	200	0.33	Chen et al. 2015
PEEK	4	0.39	Juvora Ldt, Thornton Cleveleys.
Cement (for crown)	10	0.30	Saskalauskaite et al. 2008
Ceramic crown	62	0.30	Krejci et al. 1994

RESULTS

The FEA of the models showed that the higher stress magnitude was seen in the PEEK post-core model, the stress magnitude was in the glass fiber post and composite resin core model were lower (Table 2). The maximum von Mises equivalent stress value in the zirconia post-core with thehighest elastic modulus was calculated as 21.17 MPa.

In the examination of the deformation visuals, it was observed that the stresses on post-core restorations mostly concentrated on the cervical section of the post (Figure 3). In the labio-palatal sections taken from the post-cores, the stresses consensed close to the outer surface. This concentration was also observed inside the PEEK core (Figure 4).

Table 2. Maximum and minimum von Mises stress values (MPa) in post-core models

Von Mises Stresses	Glass fiber post-Composite core	Zirconia post-core	PEEK post core
Maximum	0.80	21.17	32.76
Minimum	0.003	0.006	0.130

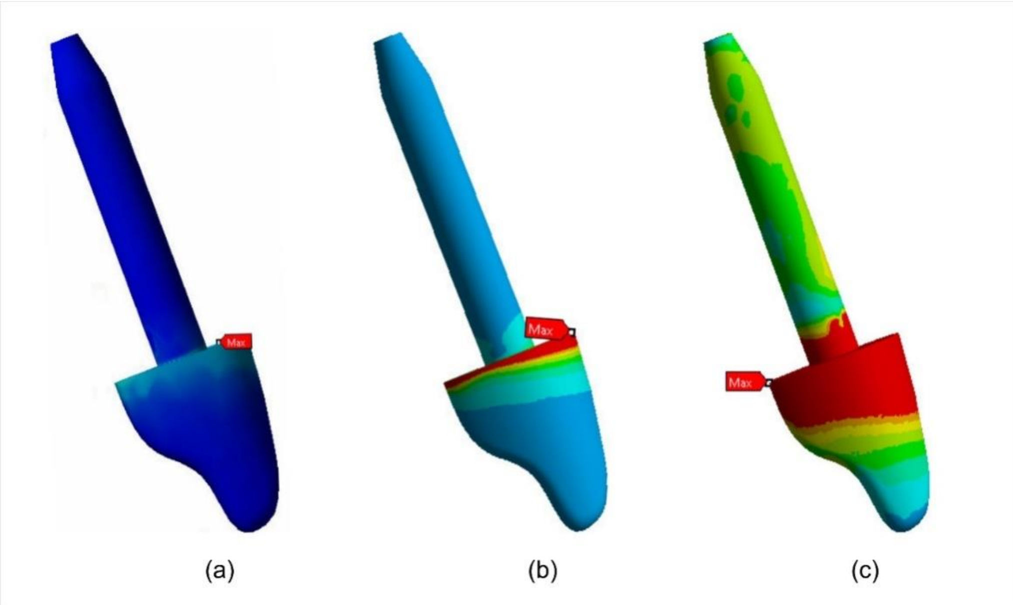

Figure 3. Von Misses stress distributions in the post-cores; (a): glass fiber post composite-resin core, (b): zirconia post-core, (c): PEEK post-core.

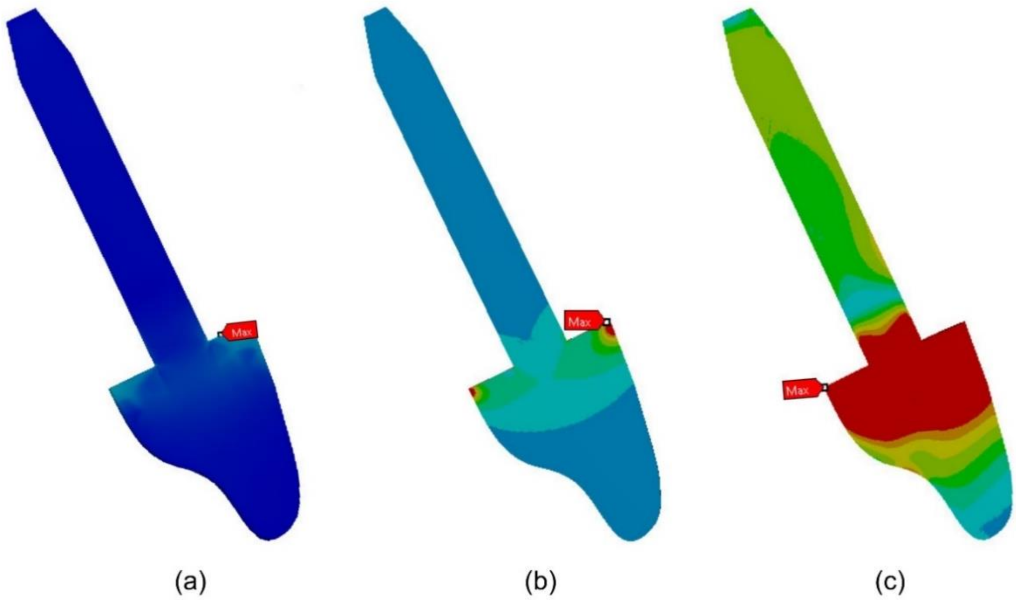

Figure 4. Von Misses stress distributions in post-cores, labio-palatal section; (a) glass fiber post-composite resin core, (b) zirconia post-core, (c) PEEK post-core.

The maximum and minimum von Mises stress values on the roots are shown in Table 3. The higher stress magnitude was seen in the root with glass fiber post, the stress magnitude was in the root with PEEK post model were lower. In the investigation of the root images, it was observed that the stresses were mostly concentrated in the cervical region of the root (Figure 5). The stresses on the labio-palatal sections extended from the cervical region to the labial face of the root (Figure 6).

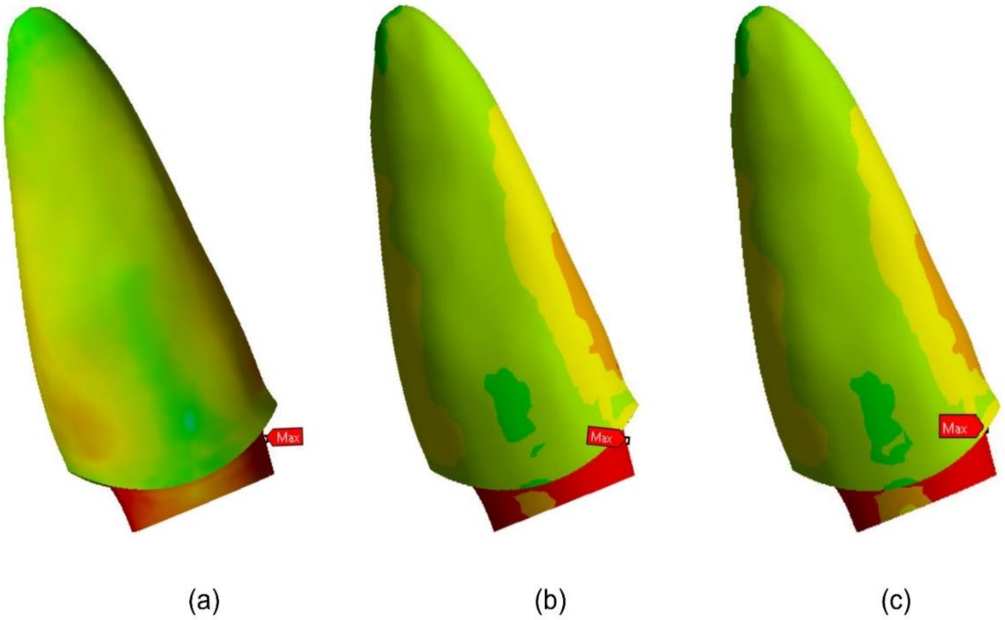

Figure 5. Von Misses stress distributions in the roots of the teeth; (a): glass fiber post applied, (b): zirconia post applied, (c): PEEK post applied tooth root models.

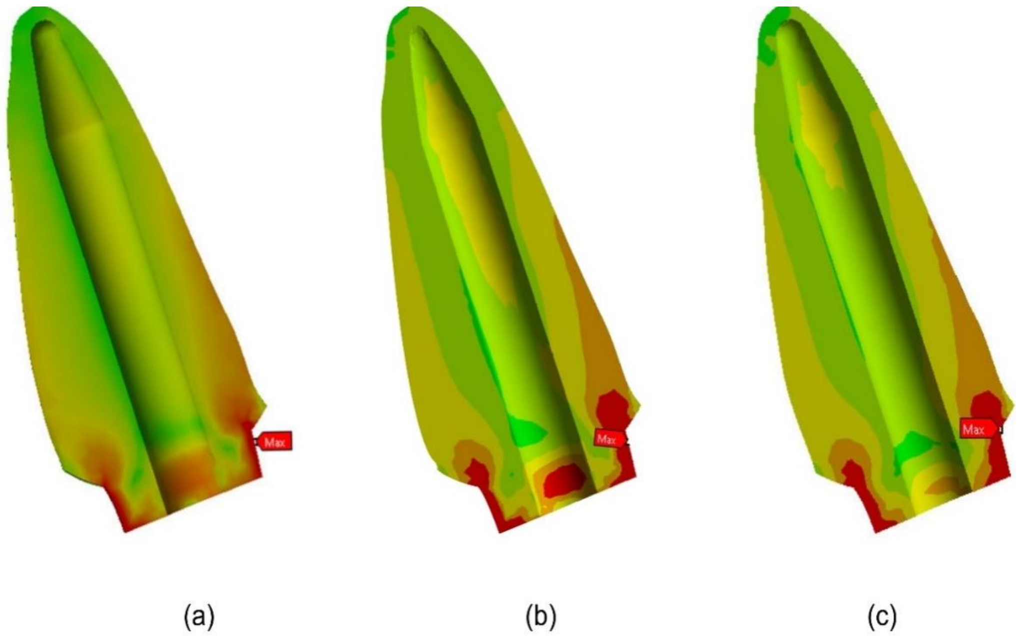

Figure 6. Von Misses stress distributions in the roots of the teeth, labio-palatal section; (a): glass fiber post applied, (b): zirconia post applied, (c): PEEK post applied tooth root models.

Table 3. Maximum and minimum von Mises stress values (MPa) on tooth root models

Von Mises Stresses	Root with glass fiber post	Root with zirconia post	Root with PEEK post
Maximum	72.80	69.01	58.22
Minimum	0.282	0.347	0.423

DISCUSSION

In this study, the structural stress magnitudes and distributions occurred on the PEEK as a post-core material for maxillary central incisor tooth by comparing with zirconia and glass fiber post-core systems were evaluated. FEA can be used to identify stress areas in a multi-component model such as a post-core restored tooth (Schmitter et al., 2006). FEA is a non-invasive and repeatable technique (Eraslan et al., 2010). In this study, 3D-FEA was preferred in order to represent a more realistic geometric model deformation and to reach more realistic numerical results (Rajambigai et al., 2016).

Root fracture is one of the most important causes of failure for teeth restored with post-core. One of the reasons for the fracture is excessive stress concentration that occurs at the apical of the post (Chan and Bryant, 1982; Dilmener et al., 2006; Komada et al., 2006). Particularly, vertical root fractures may occur when high elastic modulus post-cores such as metal, are used in the clinical routine (Komada et al., 2006). It has been reported that PEEK absorbs stresses due to its low elastic modulus (Najeeb et al., 2015). In the present study, zirconia posts were also included to investigation to compare post materials having the high and low elastic modulus (Habibzadeh et al. 2017).

It has been reported that the use of restorative materials with an elastic modulus similar to dentin structure may create a mechanically homogeneous structure (Eskitaşçıoğlu et al., 2002). Glass fiber posts have been reported to have lower stress values in dentin structure compared to zirconia posts with higher elastic modulus (Eraslan et al., 2009). The importance of harmony between restorative materials and biomechanical behavior of dental tissues has been reported (Santos-Filho et al., 2014). Similarly, another FEA study reported that materials with high elastic modulus used for restoration strongly altered the natural biomechanical behavior of the tooth (Zarone et al., 2006). In this FEA study, when the maximum stress values on post-core and tooth root were compared, the closest values were observed in the PEEK post-core model. The elastic modulus of glass fiber post was taken as 20 GPa from related literature (González-Lluch et al., 2009). Although this was the closest value to dentin's elastic modulus, the difference between the amount of stress on the glass fiber post and the root surrounding it was higher than for other materials. The maximum von Mises stress value on the root surface of zirconia post was higher than glass fiber post.

Previous studies have reported that the post-core restored tooth is mostly experienced high stresses in the cervical region (Eraslan et al., 2009; Giovani et al., 2009; Bijelic et al., 2011). In the present study, a concentrated stress was observed in the cervical region similar to the previous studies as a result of the force applied to zirconia, PEEK and glass fiber post-core restorations.

Eraslan et al. (2009) reported that stresses were more concentrated in the post part of the zirconia post model, which has a higher elastic modulus than other structures. In this respect, it is compatible with the results of Eskitascioglu et al. (2002). In a study, modeling a glass fiber and PEEK post-composite core, higher stress values were formed on the dentin compared to posts. It has been stated that PEEK posts cause less stress on dentin compared to glass fiber posts (Tekin et al., 2020). In this study, when it was compared to other material models, PEEK caused lower stress values on tooth roots with the lowest elastic modulus. Although greater stress values were seen on PEEK posts compared to fiber and zirconia posts, the manufacturer states that PEEK has high fracture resistance. Also, in another FEA study, it was stated that endodontically treated teeth restored with PEEK prefabricated posts could survive masticatory stress better than titanium and glass fiber posts. In the same study, it was stated that the stress distribution caused by the PEEK prefabricated post in intraradicular dentin exhibited a lower probability of vertical root fracture than post materials with high elastic modulus (Ibrahim et al., 2020).

Stresses on the composite core may cause treatment failure due to separation from the dentin tissue or post. In the present study, similar to the study of Tekin et al. (2020), the stresses were mostly close to the coronal area and on the core. However, in the present study, a separate core structure was created in one model. Other models were created in one piece as CAD/CAM post-core.

This study has limitations similar to several in vitro studies. It is difficult to directly match the results of this study with clinical results. The finite element model created for this study was a versatile complex structure that included full ceramic crowns, post-core restorations, endodontically treated maxillary central incisors and supporting structures. All structures were considered homogeneous, isotropic, linearly elastic and ideally bonded. The gingival line and ferrule were modelled at a constant height around the teeth. In the present study, it was possible that the stresses that occurred after applying force were affected by the materials and the individual properties of each material. Further researches were recommended including the clinical studies.

In consideration of the results extracted from this study, use of PEEK post-cores instead of zirconia and glass fiber post-cores to reduce the risk of root fractures may be suggested to the clinicians since the low elastic modulus of the PEEK. Additionally, PEEK post-core showed lesser stress distribution in the maxillary central incisor root in the present study.

Conflicts of Interest:

The authors have no conflicts of interest relevant to this article.

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