Biomechanical Analysis of Mandibular Premolar Restored with Different Custom Post Core

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Abstract

Objective This study investigated biomechanical behavior of custom post core made of six different materials on the tooth with and without the ferrule under different occlusal load.

Materials and Methods Three-dimensional models of mandibular first premolar, with and without ferrule, reconstructed from micro-computed tomography image are restored with different custom post core and zirconia crowns. By using the finite element analysis, von Mises stress shown in MPa was measured under simulated axial and oblique load of 200 [N]. To compare the stress distribution, six different custom post core materials were chosen: zirconia, Ni-Cr alloy, gold alloy, glass fiber-polyether ether ketone, polyether ether ketone, and carbon fiber-polyether ether ketone.

Results Custom post cores with a higher modulus of elasticity showed higher measured stress in the posts, but less stress in dentin. Measured stress in custom post core under oblique loading was approximately three times higher compared with axial loading. Stress in custom post core and in dentin under both types of loads was slightly higher in teeth without ferrule effect.

Conclusion The use of custom cast post cores made of different alloys is recommended in restoration of endodontically treated teeth, with extensive loss of tooth structure especially in teeth without ferrule effect.

Keywords
- endodontically treated teeth
- custom post core
- finite element analysis

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Introduction

In endodontically treated teeth, whose clinical crown is weakened or completely missing, where except function, we must ensure complex aesthetic requirements, the therapeutic choice is the fabrication of a custom post core as a foundation for prosthetic crowns.[1–4] The custom post core will ensure safe and long-term retention of fixed-prosthetic work and enable the proper transfer of occlusal load on the entire root and surrounding supporting tissues.[3,4] Today's possibilities include two therapeutic options: the use of custom post core or a prefabricated post. The amount of remaining ferrule and tooth structure is a determining factor in this choice. In a case of a greater or complete failure of a clinical crown, the choice of therapy is custom cast post core,[5] which enables close contact with the dentin walls, following its morphology, and evenly transmits occlusal forces to the remaining part of the root and the supporting tissues.[6,7] The remaining supragingival tooth structure at a height of 1 to 2 mm increases stability and resistance to fracture due to better load distribution.[8–10] The vertical axial tooth structure that will be covered by the artificial crown is called metal ring or "Ferrule effect."[9,11] Sorensen and Engelman define the "Ferrule effect" as a 360 degrees metal ring or collar of the artificial crown surrounding the parallel dentine walls in the cervical part of the crown.[12] It is considered better to have even a partial ferrule effect rather than a complete lack.[13,14] Custom cast post cores can be made of different alloys; they have a high resistance to fracture but also significantly higher modulus of elasticity than dentin. Due to the large difference between the modulus of elasticity of metal alloys compared with dentin, their use can cause stress on the root structures that can result in tooth root fracture.[15,16] Opposite of that some studies confirmed that the increased modulus of elasticity of the post reduces the stress in the dentin.[11,17] These facts are supported by studies with a follow-up period of 19.5 and 25 years, which indicate the longevity of teeth restored with custom cast post core.[18,19] Some authors presented those materials with a lower modulus of elasticity, such as fiber-reinforced composite posts (FRC posts), which lead to lower stress on the root structures and reduce the risk of root fracture, but have limited application in case of greater tooth destruction and lower resistance to fracture than custom cast post core.[5,20,21] If there is not enough coronary tooth structure or the ferrule effect is insufficient, the use of FRC posts is not indicated. In that case, they present quite high stresses in the cervical region due to their flexibility and the presence of a less stiff core material.[15,22] To achieve long-term therapy success, new materials were introduced as an option for the custom post core. One of these materials is polyether ether ketone (PEEK), a high-performance biocompatible polymer presented as a new dental material. Due to its good resistance to fracture and ability to absorb dynamic masticatory forces, it is considered an alternative to metal.[23–25] PEEK has a low modulus of elasticity (4–6 GPa) and enables the absorption of functional stresses by transmitting the forces to the tooth-supporting tissue, which is why some authors recommend them for making endo-crowns in significantly weakened teeth and to patients with parafunctions.[26–28] Its advantage is also the possibility of combining with other materials such as carbon fibers or glass fiber that greatly improve mechanical properties especially modulus of elasticity.[27–29] PEEK composites reinforced with carbon fibers (CFR-PEEK) have elastic modulus 18 GPa and PEEK composites reinforced with glass fiber (GFR-PEEK) have approximately 12GPa.[27–29]

Today, they are used in dentistry for healing caps, temporary abutments, implant-supported prostheses, other dental restorations, and computer-aided design/computer-aided manufacturing framework fabrication. Considering the biocompatibility, good mechanical characteristics, and the possibility of fabrication processing including milling and pressing, this makes this material attractive to produce individual custom posts.[24,25,28–31]

However, there is a small number of studies on this new high-performance PEEK polymer as a custom post core material, which will be analyzed in this research.

Aim of Study

The aim of this study is, by using the finite element analysis (FEA), to evaluate the biomechanical behavior of custom post core made of six different materials, on mandibular first premolar with and without the ferrule effect, under different masticatory loads.

Materials and Methods

The mandibular first premolar was scanned by micro-computed tomography scanner (SkyScan 1076 Kontich, Belgium). Three-dimensional modeling was performed using Siemens NX and Dassault System Catia software packages. The resulting model consisted of enamel, dentin, pulp, periodontal ligament, and reconstructed segment of alveolar bone. Using the AnsysWorkbench program package, a mesh of a complex model was formed, by dividing the tooth model into finite elements: for volumetric bodies mesh type Solid 187, for contact areas mesh type Targe 170 and Conta 174, and for boundary conditions and the area of force action network type Surf 154. When creating the model, the size of the basic element was 0.2 [mm], so the model consisted of 254.781 nodes or 143.664 elements (►**Fig. 1**). Two types of models were made: teeth with custom post core, with and without ferrule. To compare the stress distribution in different custom post core, six different materials were chosen: zirconia, Ni-Cr alloy, gold alloy, GFR-PEEK, PEEK, and CFR-PEEK. A zirconia fully-anatomical crown of the mandibular first premolar was modeled. A layer of glass ionomer cement with a thickness of 0.1 mm was also modeled, which was located between the custom post and the root dentin as well as the extra coronal part of custom post and the zirconia crown. The materials used in this research are linearly elastic, homogeneous, and isotropic. Since the intensity of occlusal force and teeth contact surface is extremely variable, two occlusal contact types were chosen. The stress of the simulated axial and oblique load was 200 N[32–35] (►**Fig. 2A** and **B**).

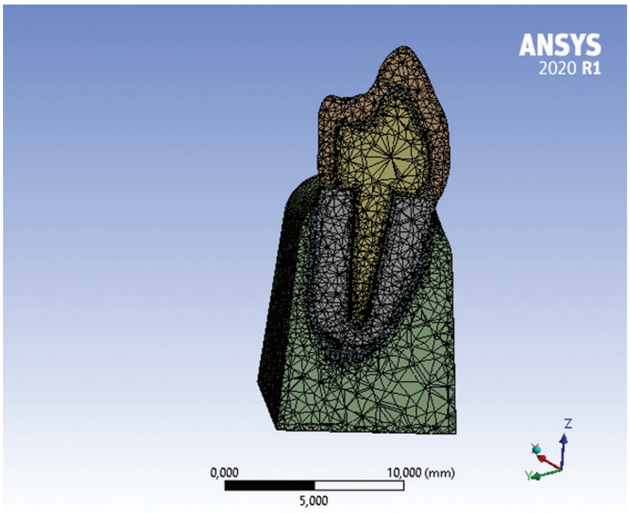

Fig. 1 Finite element mesh.

The values of the measured stress are shown by von Mises criteria that are a formula for combining the three principal stresses into an equivalent stress. Properties of the tooth tissues and used materials are given in ►**Table 1**.[17,23,30,36–43] The results obtained by the FEA represent the stress distribution values measured on dental tissues and custom post core. All research results are presented graphically with numerical stress values (on the left side of the image) and in tables. Standard statistical tests do not apply to this type of research.

Results

Von Mises stress values obtained in MPa are presented in tables and figures (images) with numeric values (on the left side of the image). The highest concentration of stress under axial load was measured in a zirconia post of 61.8 MPa in teeth with a ferrule and 62.8 MPa in teeth without a ferrule (►**Tables 2** and **4**). Under oblique load, measured stress values in a zirconia post were 191.7 MPa in teeth with ferrule and 192.5 MPa in teeth without ferrule (►**Tables 3** and **5**, ►**Fig. 3A**–D). Under an axial load, the measured stress of the Ni-Cr alloy was 60.6 MPa in teeth with the ferrule and 62.1 MPa without ferrule (►**Tables 2** and **4**). Under oblique load, the stress in the Ni-Cr alloy post was 187.3 MPa in teeth with ferrule and 188.1 MPa in teeth without ferrule (►**Tables 3** and **5**).

Table 1 Properties of the tooth tissues and used materials in 3D model

Material	Young's modulus of elasticity (GPa)	Poisson's coefficient	Reference
Dentin	18.6	0.31	36
Periodontal ligament	0.05	0.49	37
Alveolar bone	13.7	0.30	38
Glass ionomer cement	4	0.35	39
Zirconia	210	0.32	40,41
Ni-Cr alloy	203	0.30	42
Gold alloy	95	0.33	17
GFR-PEEK	12	0.40	23,30
PEEK	5.1	0.30	30,43
CFR-PEEK	18	0.39	23,30

Abbreviations: 3D, three-dimensional; CFR-PEEK, carbon fiber-polyether ether ketone; GFR-PEEK, glass fiber-polyether ether ketone; PEEK, polyether ether ketone.

Stresses measured in the dentin of teeth with a ferrule effect under oblique loading with a zirconium and CR-Ni alloy post were equal (48.3 MPa). Stress in dentin with a gold post was 49 MPa, which is approximately 1.6 times higher compared with the stress of dentin under axial force (►**Table 3**). Slightly higher stress was measured in dentin under paraxial load in CFR-PEEK post of 56 MPa, and GFR of 59.4 MPa, which is approximately two times higher

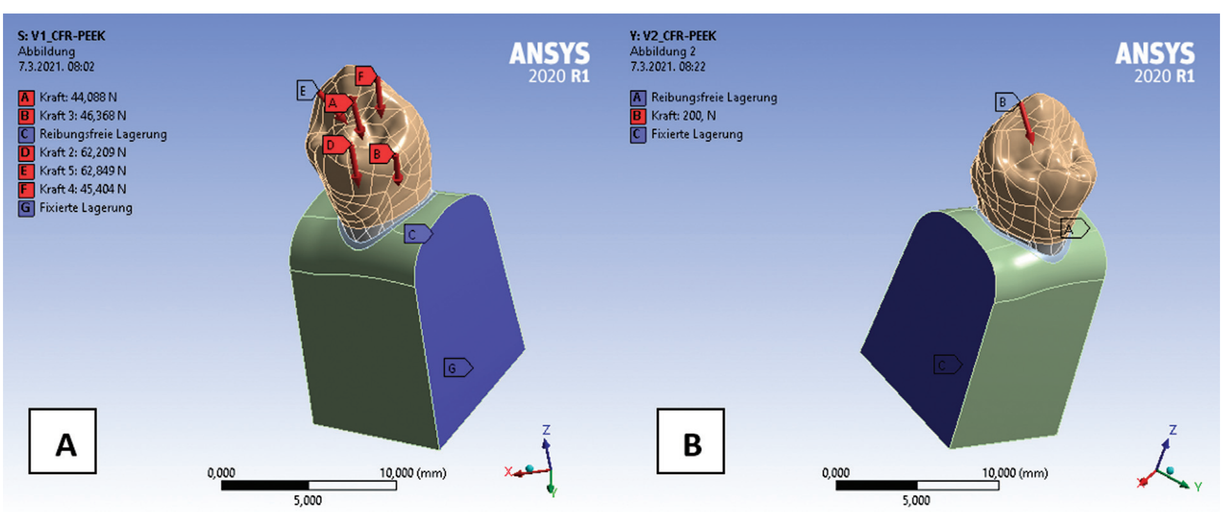

Fig. 2 (**A**) Axial tooth load and (**B**) oblique tooth load. CFR-PEEK, carbon fiber-polyether ether ketone.

Table 2 Stress values under axial load in the cast post core and dentin with ferrule

Von Mises stress	CFR-PEEK	Zirconia	Cr-Ni alloy	GFR-PEEK	PEEK	Gold alloy
Post (MPa)	9.4992	61.768	60.565	6.7665	3.5429	36.291
Dentin (MPa)	28.665	29.590	29.577	28.601	29.898	29.234

Abbreviations: CFR-PEEK, carbon fiber-polyether ether ketone; GFR-PEEK, glass fiber-polyether ether ketone; PEEK, polyether ether ketone.

Table 3 Stress values under oblique load in the cast post core and dentin with ferrule

Von Mises stress	CFR-PEEK	Zirconia	Cr-Ni alloy	GFR-PEEK	PEEK	Gold alloy
Post (MPa)	28.420	191.650	187.34	22.577	14.330	101.29
Dentin (MPa)	55.93	48.315	48.301	59.416	69.424	49.200

Abbreviations: CFR-PEEK, carbon fiber-polyether ether ketone; GFR-PEEK, glass fiber-polyether ether ketone; PEEK, polyether ether ketone.

Table 4 Stress values under axial load in the cast post core and dentin without ferrule

Von Mises stress	CFR-PEEK	Zirconia	Cr-Ni alloy	GFR-PEEK	PEEK	Gold alloy
Post (MPa)	9.7457	62.794	62.137	7.7526	5.1363	37.816
Dentin (MPa)	31.661	32.905	32.890	31.548	31.458	32.459

Abbreviations: CFR-PEEK, carbon fiber-polyether ether ketone; GFR-PEEK, glass fiber-polyether ether ketone; PEEK, polyether ether ketone.

Table 5 Stress values under oblique load in the cast post core and dentin without ferrule

Von Mises stress	CFR-PEEK	Zirconia	Cr Ni alloy	GFR-PEEK	PEEK	Gold alloy
Post (MPa)	29.523	192.49	188.17	22.764	13.999	101.58
Dentin (MPa)	57.359	51.071	51.059	60.232	70.699	51.148

Abbreviations: CFR-PEEK, carbon fiber-polyether ether ketone; GFR-PEEK, glass fiber-polyether ether ketone; PEEK, polyether ether ketone.

compared with axial force. The highest stress values were measured in dentin with a PEEK post of 69.4 MPa, which is 2.3 times higher than the stress obtained under axial force (►**Table 3**, ►**Fig. 4A–D**). Posts with a higher modulus of elasticity in teeth with a ferrule effect under paraxial loading produced lower stress values in the dentin. In gold alloy post, whose modulus of elasticity is twice as low compared with zirconia and Ni-Cr alloy, the stress of 36.3 MPa was measured in teeth with ferrule and 37.8 MPa without ferrule (►**Tables 2** and **4**). Under oblique load, the measured stress in the gold alloy post was 101.3 MPa for teeth with ferrule and 101.6 Mpa without the ferrule (►**Tables 3** and **5**). Posts made from PEEK, CFR-PEEK, GFR PEEK, and PEEK showed the lowest measured stress values under axial load, 3.5 MPa for teeth with a ferrule, and 5.1 MPa without ferrule (►**Tables 2** and **4**). Under oblique load, the measured stress in a PEEK post was 14.3 MPa in teeth with ferrule and 14 MPa without ferrule. The measured stress in posts under oblique load was approximately three times higher compared with axial load (►**Tables 3** and **5**, ►**Fig. 4A–D**). Stress measured in dentin in teeth with ferrule effect under axial load was equal in teeth with zirconia post and Ni-Cr alloy post of 29.6MPa, followed by stress in teeth with gold alloy post of 29.2 MPa. CFR-PEEK and GFR-PEEK posts had slightly lower stress in dentin, 28.7 MPa, while the PEEK post caused a slightly higher dentin stress of 30 MPa (►**Table 2**). Differences in obtained stress values in dentin in teeth with a ferrule effect after application of different types of custom post core under axial load did not prove to be significant, considering that the difference in stress values was only 1 to 2 Mpa (►**Fig. 5A–F**).

The measured stress values in the cement layer are five times higher under paraxial loading. Differences in stress values measured in cement when using different post core systems are considered insignificant.

Total stress distribution in the tooth under oblique load with six tested materials (CFR-PEEK, zirconium, Cr-Ni, GFR-PEEK, PEEK, gold alloy) was shown in ►**Table 6**.

Discussion

During the restoration of endodontically treated teeth with an appropriate post that differs from the natural dental tissues, there is a change in stress distribution within the dental structures.

The mandibular first premolar is a specific tooth in form and function. It could be considered as a transitional form between the lower canine and the mandibular second premolar because it has some characteristics of both. Due to the lingual inclination of its crown, its occlusal surface does not lie perpendicular to the long axis of the root. Having in mind the prominent crown inclination of the first mandibular premolar and its specific contact area, it is easy to pose the

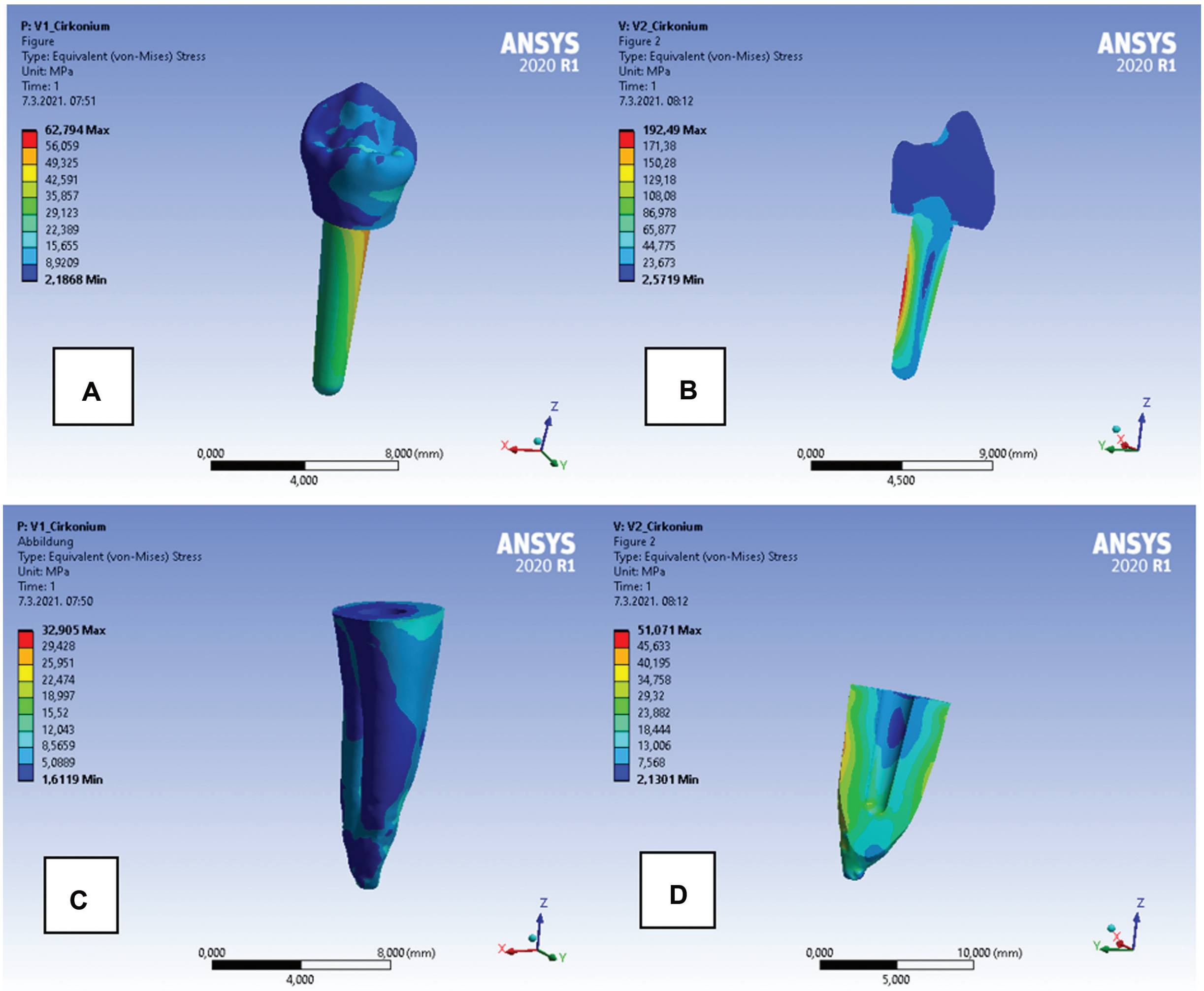

Fig. 3 (A–D) Stress distribution in the custom post core and dentin without ferrule under two types of loading.

question on their contribution to the mechanism of the distribution of occlusal forces.[44]

The anatomy of premolars and the location of the masticatory load may increase the fracture likelihood of restorations.[45]

Posts have different rigidity and modulus of elasticity from dental tissues, which could be the reason for stress concentration within the tooth root structure.[30,46–49] The FEA indicates maximum stress locations and identifies areas that could lead to failure of restorations. von Mises stress shows how stress is transferred within a body structure, without specifying its compressive or tensile nature.[50] In this research, the obtained stress in the custom post core is proportional to the increase in the modulus of elasticity of the material, while the stress in the dentin is inversely proportional to the modulus of elasticity. Similar results are presented by de Andrade et al who concluded that the stress values in the post increase with the increase in the elastic modulus of the material.[51] The results of Nahar et al. are similar to our results, where the CFR-PEEK post had stress values of 6.7 MPa, GFR-PEEK of 4.5 MPa, and PEEK of 2.2 MPa. With CFR-PEEK, due to its higher modulus of elasticity, dentin stress values of 20.2 Mpa were recorded, which is slightly less (0.2 Mpa) than the stress obtained on teeth with other custom post cores. The values of the occlusal load by Nahar et al were 100N, while in our study the values were 200 N.[30] In the study by Jafari et al, similar stress values were measured in the root dentin of Ni-Cr alloy posts and zirconia posts. The use of FRC posts in teeth without ferrule results in lower stress values along the post, but higher stress in the simulated region of the tooth, which supports the conclusion that their use is not indicated in teeth without a ferrule.[5,11,22] Durmuş and Oyar state that the highest stress values in the weakened root were measured in the tooth with carbon fiber post, while the Ni-Cr alloy posts showed the lowest stress values in the weakened root. The authors conclude that materials with a high modulus of elasticity cause less stress in the weakened root, but greater stress in the post itself.[52] Dejak and Młotkowski, Nishioka et al, Eskitaşcioğlu et al, and Asmussen et al reported that increased modulus of elasticity of the post reduces stress in dentin. FRC post produced higher stress transmitted to the surrounding dentin compared with the Ni-Cr post. The authors state that teeth restored with cast post cores have a higher fracture resistance than teeth restored with FRC posts.[17,40,53,54] In endodontically treated teeth laboratory strength tests show that a statistically

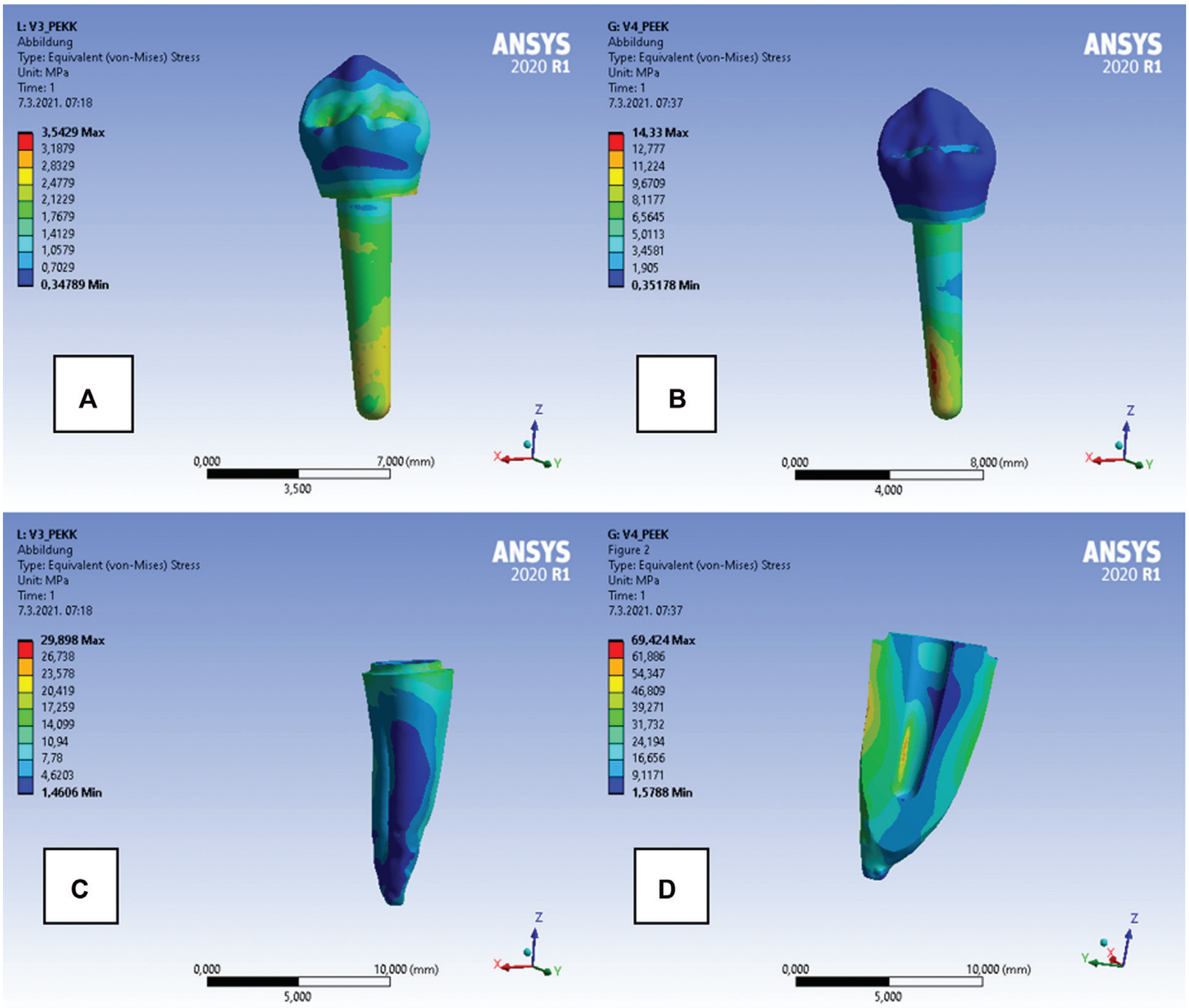

Fig. 4 (A–D). Stress distribution in the custom post core and dentin with ferrule under two types of loading. PEEK, polyether ether ketone.

higher force is required to cause tooth fracture restored with individual cast posts compared with FRC posts.[55,56] The results of Badami et al showed that custom post cores made of different materials lead to lower stresses compared with prefabricated posts.[57] In our study, the stress measured in the dentin of teeth without ferrule effect under axial load was slightly higher in all tested materials compared with teeth with ferrule. The measured stress in dentin for the zirconium and the Ni-Cr alloy post was 33 MPa, gold alloy post 32.5 MPa, CFR-PEEK, and GFR-PEEK posts 31.6 MPa, and PEEK posts 31.5 MPa, respectively (►**Table 4**). Obtained stress values in dentin under oblique load in teeth without a ferrule with zirconia, Cr-Ni, and gold alloy post were 51 MPa, CFR PEEK 57.3 MPa, GFR-PEEK 60 MPa, while the highest stress recorded in the dentin was with the PEEK post 70.6 MPa (►**Table 5**). Posts with a higher modulus of elasticity (zirconium, Cr-Ni, and gold) caused approximately 7 to 10 MPa less stress in the dentin than the CFR and GPR posts, and for approximately 20 MPa less stress than PEEK post under paraxial load in teeth without ferrule effect (►**Table 5**). The results of our research are in accordance with Sarkis-Onofre et al who proved that posts with a high modulus of elasticity show better performance in teeth that do not have a ferrule effect.[58] Teeth without ferrule effect have slightly higher measured stress values for all types of custom post core, which confirms their use in case of greater loss of tooth tissue, considering that they evenly transfer the load to the root and the supporting structures.[6,7] The better adaptability of the custom cast post helps in resistance to torsional stress and rotational forces.[59] Teeth with ferrule and cast metal posts are the most resistant to fracture.[60] Due to its composition, zirconium posts cannot be etched with hydrofluoric acid, nor can it be silanized due to its resistance to acids and the lack of silicon dioxide content,[61,62] so they do not achieve a micromechanical bond with the composite types of cement. In recent years, various surface treatments have been proposed, such as airborne particle abrasion with alumina particles, tribochemical silica coating tribochemical silica coating, laser irradiation, or chemical etching, which lead to an increase in the surface roughness of zirconium oxide, improving the micromechanical bond between cement and zirconia.[63–68] However, various studies have reported possible damage to the surface of zirconia caused by air-abrasion methods.[66,67,69] To overcome this problem,

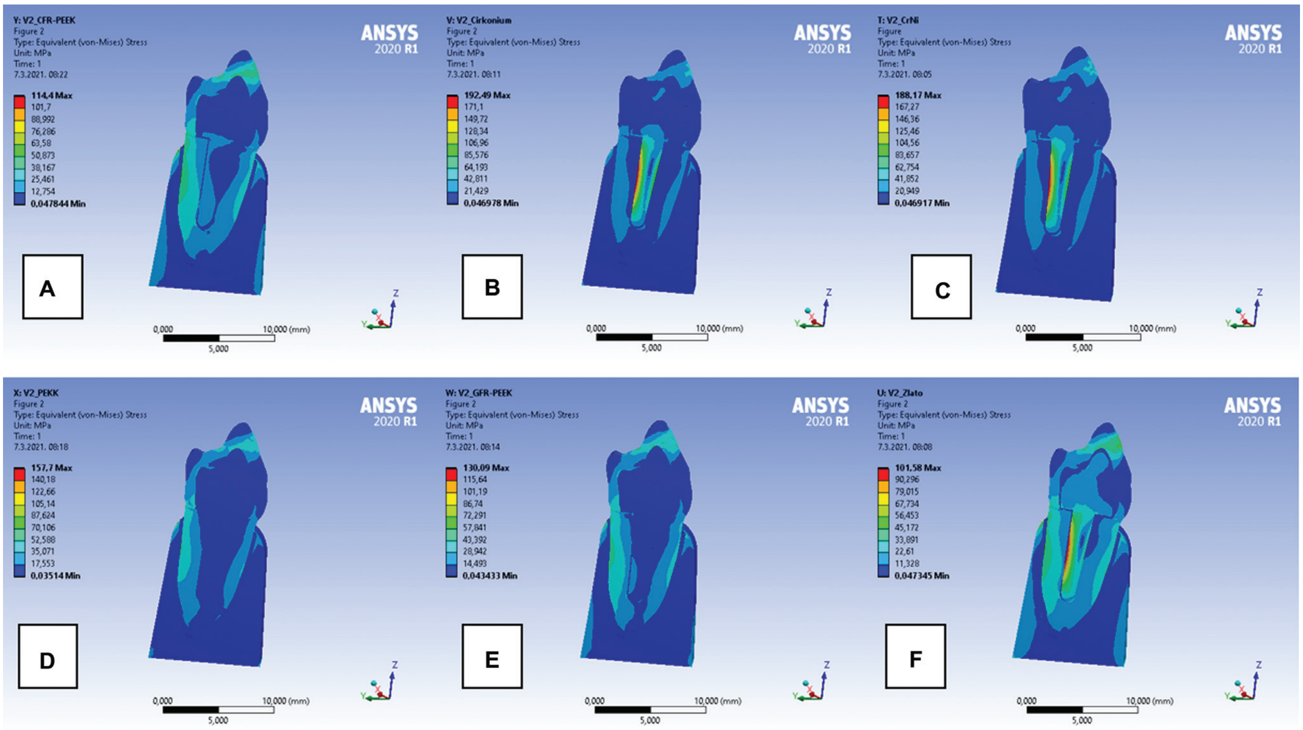

Fig. 5 Total stress distribution in the tooth under oblique load with six tested materials: (A) CFR-PEEK, (B) zirconium, (C) Cr-Ni, (D) GFR-PEEK, (E) PEEK, and (F) gold alloy. CFR-PEEK, carbon fiber-polyether ether ketone; GFR-PEEK, glass fiber-polyether ether ketone; PEEK, polyether ether ketone.

Table 6 Total stress in the tooth under oblique load with 6 tested cast post cores (MPa)

CFR-PEEK	Zirconia	Cr-Ni alloy	GFR-PEEK	PEEK	Gold alloy
114.4	192.49	188.17	157.7	130.09	101.58

Abbreviations: CFR-PEEK, carbon fiber-polyether ether ketone; GFR-PEEK, glass fiber-polyether ether ketone; PEEK, polyether ether ketone.

alternative methods are introduced such as chemical promoters and zirconium-specific organophosphate/carboxylic acid monomer resin cements, which are considered chemical surface treatments.[67,70] However, hydrolytic degradation is still problematic, as is the bond of zirconia to composite cement.[67] Zirconia custom post core and peek custom post core can be made with CAD/CAM technology using "additive" or "subtractive" manufacturing methods.[59] CAD/CAM technology reduces the number of patient visits to the office and allows faster production of dental restorations with higher mechanical strength compared with hand-made ceramic restorations.[71] Due to the weak connection and adaptation of zirconia custom post core with composite types of cement, there is a possibility of the zirconia post falling out of the root canal, which gives an advantage to custom cast metal post cores. Custom cast metal post cores can be made with conventional technology and CAD/CAM technology as well. Studies by Chen et al and Hendi et al reported that CAD/CAM post core required less time to manufacture than custom cast post core, but custom cast post core had better adaptation in the root canal.[72,73] The use of CAD/CAM technology in the production of custom post core represents alternatives to conventional techniques, but there is not enough data on their clinical success, so long-term clinical studies are necessary to confirm their success.[59] PEEK has only recently been introduced as an alternative treatment option to many conventional methods. PEEK custom post core, which had the lowest modulus of elasticity, but due to the highest values of the measured stress in the dentin, is not recommended for use in the restoration of endodontically treated teeth. PEEK material reinforced with carbon and glass fibers has proven to be a better choice in the therapy of endodontically treated teeth, due to better mechanical properties and lower stress within the dentin. It is possible to consider their application in frontal teeth with ceramic crowns in situations where the aesthetic factor is dominant. However, there is still little data on their application. The total stress in the tooth supplied with the custom post core was the lowest with gold alloy, followed by PEEK materials, then Ni-Cr, while the highest total stress was measured in the tooth with zirconia post (►**Table 6**, ►**Fig. 5A–D**).

Conclusion

The stress in the custom post core under axial load is proportional to the increase in the modulus of elasticity of the material. The highest stress was measured in the zirconia post and the lowest in the PEEK post under both types of loads in teeth with and without the ferrule effect. The measured stress in the custom post core under oblique load is approximately three times higher compared with axial load. Custom post cores with a higher modulus of elasticity produced less stress in the dentin under oblique loading. The lowest stress in the dentin under paraxial load was produced by the zirconia and post made of Cr-Ni alloy and the highest by the PEEK posts. In teeth without the ferrule effect, slightly higher stress values were measured both in the custom post core and in the dentine for both types of loading. The use of custom cast post cores made of different alloys is recommended in restoration of endodontically treated teeth, with extensive loss of tooth structure especially in teeth without ferrule effect. Randomized controlled studies must be conducted to obtain data on the clinical behavior of PEEK and fiber-reinforced PEEK materials and their use in endodontically treated teeth.

Limitations of the Study

The structures and materials used in this research are considered to be linearly elastic, homogeneous, and isotropic, which is different from the natural structure of teeth and supporting tissues. In this research, a static load was applied, while in real clinical situations, there is always a dynamic loading, which leads to fatigue of the material and eventual fracture of the root.

Authors' Contributions

All authors have equally contributed to the concept and design of the study, analysis, and interpretation of the data, literature search, and writing the manuscript. All authors have revised the manuscript critically for important intellectual content, and all authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

None declared.

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