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Research article

Evaluation of stress distribution on an endodontically treated maxillary central tooth with lesion restored with different crown materials: A finite element analysis

Ömer Kirmali [a,*], Gülsah Icen [a], H. Kursat Celik [b], Allan E.W. Rennie [c]

[a] Department of Prosthodontics, Faculty of Dentistry, Akdeniz University, Antalya, Turkey
[b] Dept. of Agr. Machinery and Technology Engineering, Akdeniz University, Antalya, Turkey
[c] School of Engineering, Lancaster University, Lancaster, United Kingdom

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ABSTRACT

Objectives: The biomechanical response of teeth with periapical lesions that have been restored using various substructure materials, as well as the stress mapping in the alveolar bone, has not been thoroughly described. In this context, the objective of this study is to investigate the structural stress distributions on root canal-treated maxillary right central incisors with lesions restored using different crown materials under linear static loading conditions through finite element analysis (FEA).

Methods: In the study, five FEA models were utilised to represent healthy teeth and teeth restored with different substructure materials: (A) a healthy tooth, (B) a lesioned, root canal-treated, composite-filled tooth, (C) a lesioned, fiber-posted, zirconia-based crown, (D) a tooth with lesions, a fiber post, and Ni–Cr infrastructure crown, (E) a tooth with a lesion, a fiber post, and an IPS E-max infrastructure crown. A force of 100 N was applied at an angle of 45° to the long axis of the tooth from 2 mm cervical to the incisal line on the palatal surface. Deformation behaviour and maximum equivalent stress distributions on the tooth sub-components, including the bony structure for each model, were simulated.

Results: Differences were observed in the stress distributions of the models. The maximum stress values of the models representing the restorations with different infrastructures varied, and the highest value was obtained in the model of the E-max crown (Model E: 136.050 MPa). The minimum stress magnitudes were obtained from Model B the composite-filled tooth (80.39 MPa); however, it was observed that the equivalent stresses in all the models showed a similar distribution for all components with varying magnitudes. In periapical lesion areas, low stresses were observed. In all models, the cervicobuccal collar region of the teeth had dense equivalent stresses.

Conclusion: Different restorative treatment methods applied to root canal-treated teeth with periapical lesions can impact the stress in the alveolar bone and the biomechanical response of the tooth. Relatively high stress values in the cortical bone at the cervical line of the tooth have been observed to decrease towards the apical region. This observation may suggest a potential healing effect by reducing pressure in the periapical lesion area.

Clinical significance: Composite resin restorations can be considered the first-choice treatment option for the restoration of root canal-treated teeth with lesions. In crown restorations, it would be advantageous to prefer zirconia or metal-supported prostheses in terms of biomechanics.

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* Corresponding author.
E-mail address: omerkrml@ymail.com (Ö. Kirmali).

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1. Introduction

Today, dental caries are among the diseases that still maintain their prevalence, for which their effects are mostly addressed with root canal treatment (RCT) [1,2]. RCT has been successfully applied in dentistry for many years. The factor that determines the prognosis of the tooth is whether the RCT was performed perfectly. Many factors, such as the amount of impact on all structures, including the existing tooth, the hard and soft tissues around it, and the restorative treatment after endodontic treatment, are effective [2].

Periapical lesions are inflammatory disorders associated with teeth with infected and necrotic pulp. They give a radiolucent image in radiographs taken from the related region due to bone destruction around the apical lesion [3]. Follow-up monitoring or treatment of teeth with lesions may require a long period of four years [4]. This situation makes the anterior region, which is very important for the patient in terms of aesthetics, function, and phonation, even more crucial.

Teeth subjected to RCT are more susceptible to fractures for several reasons (fractures, caries, loss of dental tissue during restorative treatment, and idiopathic reasons) [5,6]. Therefore, it is intended that the biomechanical performance will be better understood thanks to the restorations applied after the treatment [7]. Post applications are often necessary to increase the retention of the coronal restoration and to create a strong structure [8,9]. One of the most common complications in post applications is root fractures caused by the difference in elastic modulus between dentin and the post material [10]. Research has reported that post systems with an elastic modulus closer to natural teeth reduce the probability of failure [11]. Fiber post systems have been successfully applied for this purpose, owing to their aesthetic and dentin-like properties [12,13].

Dental porcelains are generally used in conjunction with a solid infrastructure. For this purpose, metal-based ceramics have been used for many years [14]. Thanks to the metal infrastructure used, the restoration gains resistance, and porcelain fractures that may occur due to external forces are prevented. However, alternative materials have also been developed due to issues such as allergic tissue reactions, corrosion, galvanic current, radiopaque appearance, etc. [15]. As a consequence of the increasing cosmetic demand by patients, there is a tendency towards more aesthetic prosthetic materials. Zirconia is one of the latest materials to be added to ceramic restorations [16]. Zirconia is a material with superior properties such as being biocompatible, tough fracture resistance, and high resistance [17]. It also helps to achieve a more natural color and form because of its relatively better light transmittance compared to metal-supported restorations [18,19]. There are also all-ceramic systems that do not contain a metallic infrastructure and are developed to provide better light transmission and aesthetics [20]. E-max crowns are full ceramic with aesthetic properties close to natural tooth tissues, thanks to their longevity and glassy structure. They represent a preferred category of dental crowns.

While various ceramic systems are employed, an analysis of the literature and information derived from clinical applications reveals that there is no singular universal material or system suitable for every case [21]. In addition, it has been concluded that different properties of these materials come to the fore under varying loads [22]. Here, the FEA technique is widely used as an excellent tool to predict long-term problems in certain regions of materials and to provide additional data for in vitro tests [23].

In the literature, there are studies investigating various post or crown options for RCT-treated teeth [8–13]. However, no study has evaluated prosthetic restorations on teeth with lesions treated with RCT and fiber posts. The aim of this study is to examine the stress distributions of RCT-treated right central incisors with lesions under static load by using FEA. The null hypothesis of the study is that prostheses with different crown infrastructures in teeth with periapical lesions will not affect the biomechanical response created by the changing dental components and alveolar bone.

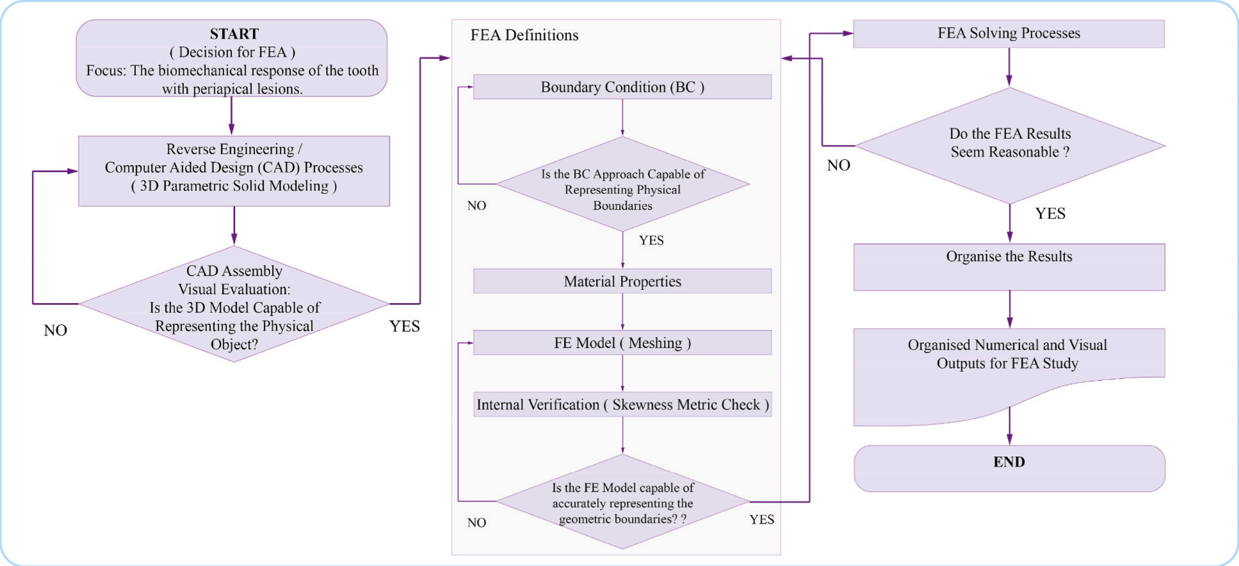


Fig. 1. Application algorithm for FEA

2. Material and method

2.1. Application algorithm for FEA

In this study, an application algorithm was introduced based on the recognised standard FEM strategy, which can be incorporated into FEA studies to investigate applicable biomechanics in dentistry. This algorithm was utilised in a study examining the biomechanical response of teeth with periapical lesions that were restored using different substructure materials. The algorithm was formulated using Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) techniques. The fundamental application sequence of the algorithm is depicted in Fig. 1.

2.2. Identifying structural components and creating the master model

In this study, analyses based on the finite element method (FEM) were employed to examine the maxillary right central incisor. The tooth geometry was generated using real-size 3D digital models of human tooth provided by the School of Dentistry at the University of Dundee in Scotland. The digital model served as the reference for the study. The procedures for root canal treatment, post placement, core restoration, and crown application were carried out using SolidWorks, a 3D computer-aided design (CAD) parametric solid modeling software (SolidWorks Corp. in Massachusetts, USA) [23–28].

The structural analyses were conducted using the commercial FEM code ANSYS Workbench (ANSYS, Canonsburg, USA), relying on several fundamental assumptions; (a) The geometry of the models featuring the post-core-crown geometry was simplified to ensure symmetry across the vertical mid-axis for all components. (b) Cementum, a thin layer of root anatomy, was treated as continuous with root dentin. (c) All components were assumed to be without gaps, in contact, and perfectly connected. (d) The outermost surface of the alveolar (trebecular) bone was fixed to prevent displacement. (e) Normal pre-stresses potentially arising from root canal treatment were disregarded. (f) All materials were treated as linear, homogeneous, and isotropic. Moreover, all FEA scenarios were conducted utilising an implicit analysis approach, which is better suited for addressing static or slowly dynamic problems characterized by low strain rates.

First, a lesion-free tooth model with healthy enamel, dentin, and pulp was established. Subsequently, to assess the impact of various crown alternatives following root canal treatment (RCT) on compromised teeth, a tooth model was generated. This model underwent restorative treatment using composite resin after the RCT application.

The structures, in which the dentin component is in contact, were planned to be fully connected with the crown, enamel, cement, pulp, post, core, luting cement, and gutta-percha (GP). In clinical applications, it is recommended to maintain a 4 mm GP in the apical region while creating the post space after RCT [25]. In the created models, the length of the apical region of the GP was 4 mm (The periapical lesion was determined as 4 according to the PAI index (Periapical destruction of bone probably present) [29], with a distance of 1 mm between the apical end and the GP. The periodontal ligament (PDL) was constructed with a thickness of 0.2 mm.

For models C, D, and E, the post form was determined simultaneously, and the apex was designed in a conical shape (Para Post Fiber White, Coltène/Whaledent, Mahwah, USA). The ferrule length was established as 1.5 mm. All root formation was deemed dentin, and cement thickness was disregarded.

Post-dentin cement was determined as 50 μm, dentin-crown cement as 30 μm thick, and dual cure resin cement as Ivoclar Vivadent (Schaan, Liechtenstein). Components of core structure included dental ferrules (dentin tissue), coronal fiber post and composite resin (Para Post Fiber White, Coltène/Whaledent, Altstatten, Switzerland). The crown design was determined to form a 1.5 mm

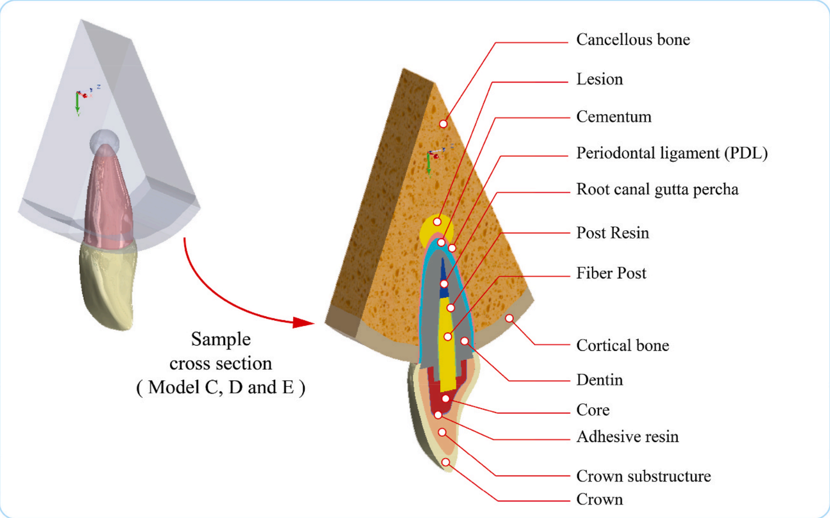


Fig. 2. Sample model configuration for Model C,D and E.

supragingival chamfer with a 2 mm incisal reduction, a 1.5 mm vestibule reduction, and a 1.0 mm interproximal and lingual reduction. The infrastructure thickness of all of the crown designs, was determined to be homogeneous and 0.5 mm. Dental porcelain formed the remaining coronal superstructure. A sample tooth model and its sub-components employed in the FEA study was illusrated in Fig. 2.

Upon the formation of healthy and RCT tooth models (Models A and B), a total of five clinical scenarios were created by designing the models of crowns with zirconia, metal (Ni–Cr), IPS E-max infrastructure materials so that their mechanical behaviors were compared after occlusal loading. Cross section views of the models A,B,C,D and E are shown in Figs. 3 and 4.

2.3. Boundary conditions

During the FEA setup, the contact relations between all components were assigned with bonded contact definitions under the assumption of full (100%) contact. Additionally, the bone structure were fixed. Consistent with comparable studies in the literature, a force of 100 N was applied to the palatal surface at a 45° angle to the tooth's long axis, starting 2 mm cervical to the incisal line [30–36].

2.4. Material properties

Material parameters, including the elastic modulus, Poisson's ratios, and material density, were assigned to the pertinent components of the tooth models. The elastic modulus of dentine was assigned a magnitude corresponding to traditional dentine without sclerosis. Nevertheless, when contemplating teeth subjected to secondary retreatments or within an aging population, this modulus could experience a change. However, for the purposes of this study and in accordance with the material model assumption applied in FEA, we adopted an approach utilising the homogeneous isotropic linear elastic material model, maintaining a constant value for the elastic modulus [37]. Reference values for the physical description of the periapical lesion were derived from previous FEA studies, including pulpal values associated with lesions (Table 1) [38,39].

2.5. FE model (meshing)

The finite element (FE) model structure (meshing) of the solid models was created using the FEM code meshing interface. The quality of the network structure between elements was maintained at the highest possible level. The skewness mesh metric scale was employed for internal verification of the FE model. The finite element quality of the models exhibited an average skewness metric of 0.234, indicating excellent mesh quality [40,41]. On average, there were a total of 898336 elements and 1342325 nodes (Fig. 4).

3. Results

When a total of five model scenarios (healthy, RCT, fiber post, and crown restoration tooth models) were examined, it was observed that the stresses formed after occlusal load applications concentrated in similar regions in all models. The stress and deformation printouts, extracted from the FEA, are shown in Fig. 5 (Models A-E). The region where the maximum equivalent stress occurred was the buccal cervical region. Component-based numerical deformation and stress results obtained from the FEA are listed in Table 2.

When the models containing crowns were evaluated among themselves, there was no difference in the localisation of the tooth components and the stress distributions in the lesion area. While the maximum equivalent stress values of the zirconia and metal-based crown models were similar (for Models C and D, 124.64 MPa and 124.49 MPa respectivelly), the highest result was obtained in the model with the E-max crown as 136.05 MPa (Model E).

In all models with periapical lesions (Models B-E), the lesion area exhibited the same equivalent stress as the trabecular bone,

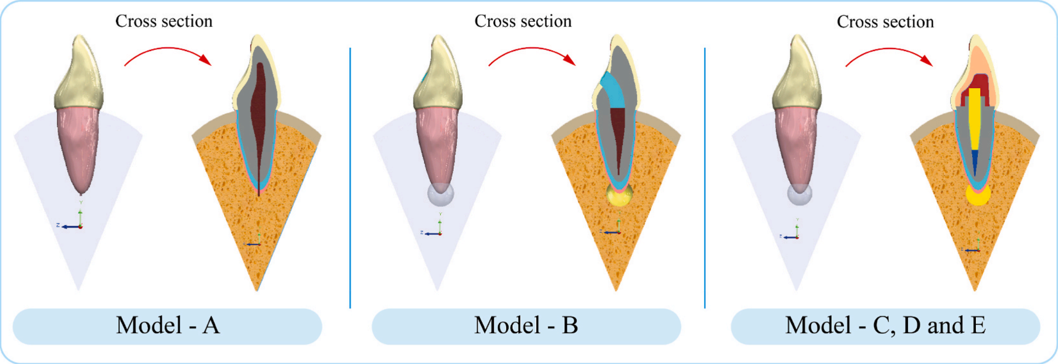
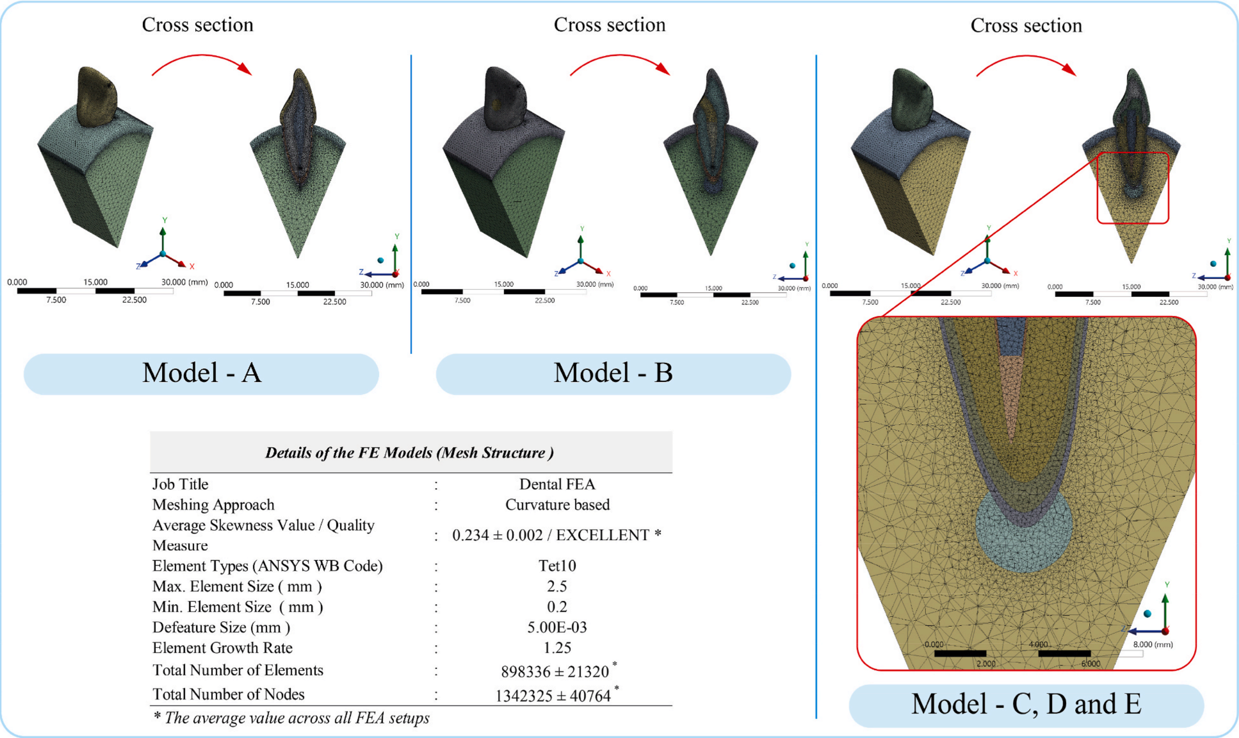


Fig. 3. FEA models (Model A: healthy tooth model; Model B: lesioned, root canal-treated, composite-filled tooth; Model C: lesioned, fiber posted, zirconia-based crown. Model D: tooth with lesions, fiber post, and Ni–Cr infrastructure crown. Model E: tooth with lesion, fiber post, IPS E−max infrastructure crown.).



Details of the FE Models (Mesh Structure)		
Job Title	:	Dental FEA
Meshing Approach	:	Curvature based
Average Skewness Value / Quality Measure	:	0.234 ± 0.002 / EXCELLENT *
Element Types (ANSYS WB Code)	:	Tet10
Max. Element Size (mm)	:	2.5
Min. Element Size (mm)	:	0.2
Defeature Size (mm)	:	5.00E-03
Element Growth Rate	:	1.25
Total Number of Elements	:	898336 ± 21320 *
Total Number of Nodes	:	1342325 ± 40764 *

** The average value across all FEA setups*

Fig. 4. FE Model (mesh structure) details.

Table 1
Material properties assigned in the FEA set up.

Material properties (FEA definitions - Homogenous isotropic linear elastic material model)			
Material	Modulus of Elasticity	Poisson's Ratio	Density
	(MPa)	**(-)**	**(kg m^{-3})**
Enamel	84100	0.33	2800
Dentin	18600	0.31	2200
Cortical bone	14000	0.323	1400
Cancellous bone	1370	0.38	850
Pulp	2.10	0.45	1000
Periodontal Ligament (PDL)	68.90	0.45	1100
Cement	8200	0.31	2030
Lesion tissue	0.69	0.45	370
Glass fiber post	37000	0.27	2500
Composite	12400	0.3	2400
Crown (porcelain)	68900	0.28	2300
Gutta-percha	0.69	0.45	370
Adhesive resin cement	7600	0.3	2000
Sub-structure (IPS E-max)	95000	0.25	2500
Sub-structure (Zirconia)	200000	0.31	5500
Sub-structure (Ni–Cr)	204000	0.3	7600

indicating low stress and deformation displacement (Fig. 5). Additionally, the stress values detected for cortical bone were higher than those detected for trabecular bone in all models. The maximum equivalent tension was consistent in all models and formed in the cortical bone in contact with the cervico-buccal bone of the tooth. While the lowest value was detected in the healthy tooth model (Model A), the highest value was observed in the model with the E max crown (Model E) (Table 2) (Fig. 5).

A decrease in stress was observed in the alveolar bone from the cervical line to the apical region. Although this situation did not exhibit homogeneity dependent on the direction of force and tooth anatomy, a significant decrease drew attention (Fig. 5).

When the simulation legend was analysed in the sagittal section of the root region of all models, the green stress areas on the buccal and palatal surfaces of the models (Fig. 5, Models C-E) with a fibre post and crown were more coronal and more visible than those in the healthy and only root canal treated (RCT) tooth models (Fig. 5, Models A and B). This was observed to be less. Additionally, in these

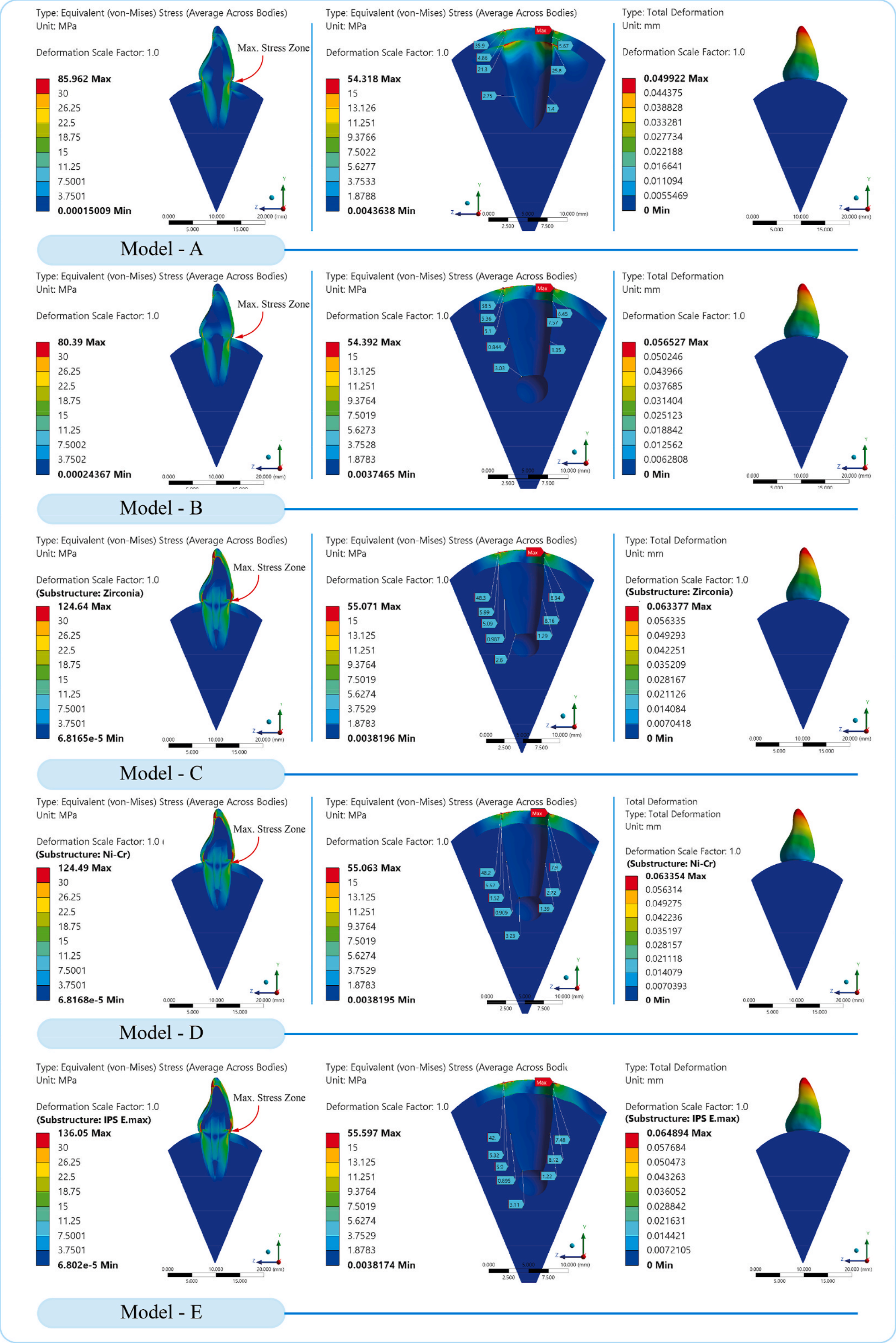


Fig. 5. The FEA output visuals.

Table 2
Numerical deformation and stress results obtained from the FEA study by components.

Output		Components	FEA Study Code				
			Model A	Model B	Model C	Model D	Model E
Max. Deformation	(mm)	Global (Whole Model)	0.0499	0.0565	0.0634	0.0634	0.0649
Max. Equivalent Stress (von Mises)	**(MPa)**	**Global (Whole Model)**	85.962	80.390	124.640	124.490	136.050
		M. Cortical Bone	54.318	54.392	55.071	55.063	55.597
		M. Trabecular (Cancellous) Bone	28.579	3.844	3.657	3.657	3.633
		Crown (Porcelain/Enamel)	85.962	80.390	124.640	124.490	136.050
		Substructure (Zirconia)	–	–	117.716	–	–
		Substructure (Ni–Cr)	–	–	–	117.831	–
		Substructure (IPS E-max)	–	–	–	–	130.470
		Lesion	–	0.050	0.015	0.015	0.015
		Fiber Post	–	–	15.924	15.927	15.663
		Dentin	33.527	34.127	52.497	52.436	56.022
		Filler/Core (composite)	–	16.704	14.484	14.499	15.307
		PDL	14.082	14.259	14.794	14.791	14.985
		Cement	24.244	23.584	40.805	40.760	43.473

models (Fig. 5, Models C-E), low-stress areas in the bowl formation in the bucco-palatal direction were observed just below the crown-root junction due to the bending stress forming depending on the effect of the moment. In all models containing a fibre post (Fig. 5, Models C-E), the post exhibited the same stress distribution in the root and crown as it was in contact with the dentin.

4. Discussion

The results of the study revealed that while there was similarity between the maximum equivalent stress values in the cervical region under occlusal load in Models C and D (Fig. 5), higher equivalent stress values were found in Model E compared to Models C and D (Fig. 5). The stresses along the root were observed at different concentrations, taking into account the geometric structure of the tooth. Also, in all models with periapical lesion (Fig. 5, Models B-E), the lesion area showed the same equivalent strain as the trabecular bone. Therefore, the hypothesis that restorations with different crown infrastructures in teeth with periapical lesions will not affect the biomechanical responses of dental components and alveolar bone was partially rejected.

The FEA method is frequently preferred in structural analysis and material studies [42]. For example, this method allows visualisation of stress distributions and corresponding values that will occur in all parts of the modeled structure, easily analyze materials with complex and irregular surface properties, make comparisons by changing the properties of the applied force, repeat the analyses, and easily simulate the interaction phenomenon between dental posts, surrounding tissues and restoration materials [43,44]. Due to all of these advantages, the FEA method was preferred in this study.

Considering the literature data and clinical applications, there are many prosthetic material options. Cervino et al. [22] concluded with their study on different materials that there was no optimal crown material and these materials had different properties under varying loads. Therefore, in this study, the effect of changing crown materials on the tooth anatomy or the stress on the periapical lesion was investigated with the FEA method that included five models.

The results of the present study revealed that in all load-applied models, the observed stresses occurred on the buccal and palatal surfaces of the crown at the level of the enamel-cementum junction. The studies have reported that stresses first appear in the application area of the load [45,46]. This situation is similar to the formation of stress fields observed in the region where the force was applied in the palatal region in all models in the present study. The FEA studies, which give similar results in the literature, have reported that when a force is applied to a restricted area, the observation of concentrations in that area exhibits this situation [47–49].

When looking at the root area, low stresses at the same level as the trabecular bone were observed in the lesion localisation. The highest stress distributions in root dentin were observed in the buccal and palatal walls, especially in the cervical and middle third. This result is compatible with the results of the model applied glass fiber post in the FEA study conducted by Coelho et al. [50] with different post types on the maxillary central incisors and the study conducted by Shetty et al. [35] on aesthetic post applications.

According to the data of the FEA study conducted on different crown alternatives in canine teeth treated with fiber-post, Moris et al. [23] found that the stress distribution in all models was similar and homogeneous throughout the fiber post, root, cement and PL. Also, the healthy tooth model showed a lower stress value compared to the endodontically treated tooth models. In this study, when the healthy tooth model (Model A) was compared with the lesioned, fiber-post, crown restoration models (Models C-E), an increase was observed with the crown restoration, which is compatible with the study by Moris et al. [23] In addition, the tensions in all models were similar and homogeneous across the fiber post, root dentin, and PL. However, Moris et al. [23] reported in their study that varying combinations of prosthetic materials showed similar stress distributions along the root length, which is compatible with the results of the present study. According to the data of the models created in the study, there was an increase in equivalent stress values in the RCT and fiber post lesioned teeth (Fig. 5, Models C-E) compared to the tooth model with only RCT and lesions (Fig. 5, Model B). This situation suggests that both biological and biomechanical evaluation should be done when choosing the treatment option in clinical applications. In cases where it is difficult to decide on crown restoration planning, the data of the present study can be used as a guide.

In a FEA study on aesthetic post systems, it was observed that the stresses in the alveolar bone for glass fiber post models were most concentrated at the cervico-buccal level of the tooth [35]. Likewise, another study conducted with different post systems [51] in glass fiber post models reported that the cervico-buccal region underwent the greatest stress concentration. On the contrary, studies investigating different clinical conditions have also reported high stress concentrations in the cervico-palatal region [26,52]. Maximum equivalent stresses were observed in the cervico-buccal region. The present study is compatible with the results of the study by Shetty et al. [35] and the study by Seo et al. [51].

The high stress concentration in the cervical region in this study is consistent with all other studies on root canal-treated fiber post [50,53,54]. This may be caused by variables such as the anatomy and designs of the tooth-bone model, the elastic modulus and poisson's ratio differences of the materials as well as the area and amount of force applied.

Due to the flexibility of glass fiber posts similar to dentin and their ability to maintain this flexibility in the core region, the stresses concentrate around the cervical region [55]. Materials with high elastic modulus can change the standard biomechanical behaviors exhibited by teeth. According to a study by Zarone et al. [54], the properties of glass fibers to have the same stiffness as the tissues they are in contact with in the root cause the stresses occurring in the root are found to be low. It was observed that it caused similar colorations according to the metric scale. These regions showed lower Von Mises equivalent stress than the other model elements.

In their study, Petcu et al. [56], noted that high Von Mises equivalent stresses occurred in the area where occlusal force is applied, as well as in the cervical region of the teeth and the bone adjacent to that area. However, this did not have a destructive effect on the tooth models, as reported by the authors. Furthermore, in the same study, the total deformation of the tooth models was examined, and the maximum deformation was observed in the incisal third of the crown, decreasing towards the apex. Despite differences in tooth model anatomies between their study and the present one, the regions where stress intensities were observed showed similarities.

The data from the present study on alveolar bone revealed the highest stresses in the cortical bone in the region close to the cervical of the tooth, aligning with the findings of Petcu et al.'s study. The values of trabecular bone along the root circumference decreased towards the apical region. The deformation data from the present study were found to be comparable to those in the aforementioned study. The observation that deformation intensifies in the incisal and decreases towards the cervical, supported by trabecular and cortical bone, indicates that the resulting deformation does not have a destructive effect on the tooth models.

Gomes et al. [25], conducted FEA studies on models having different amounts of weakened root dentin walls, including RCT maxillary canine teeth with fiber posts, and also being restored with metal-supported crowns. As a result, they reported that they showed similar stress distributions. In this study, it was found that Models C-E in Fig. 5 with a 4 mm periapical lesion with RCT and fiber post exhibited similar stress distributions. Although there are differences in the tooth number used, applied force and model planning, the data obtained are in the same direction as the models created in both studies exhibiting similar stress distributions among themselves.

According to the results of the present study, it can be asserted that composite filling restorations, which are the conventional treatment option, should be the first option instead of covering the lesioned and RCT teeth with crown prostheses by applying a post, unless it is mandatory. Although crown prosthesis application is mandatory, it will be advantageous to use zirconia or metal supported prostheses in terms of biomechanics. As the stress concentrations forming within the dentoalveolar structure can be a potential cause of failure, the results of the study revealed that it is useful in evaluating the prognosis of RCT teeth with apical lesions from a biomechanical perspective. In the future, it would be beneficial to carry out further studies on this subject and to support these studies with clinical findings.

The main limitation of this study is that intraoral conditions cannot be imitated exactly by FEA studies. In addition, the forces occurring in the oral environment have both static and dynamic structures, and the thermal transitions that occur as a result of oral activities can be considered additional limitations. Whilst the anatomical structures of the modeled teeth are not exactly the same in every person, ideal tooth forms and structures are examined by standardizing them in these studies. While FEA studies are conducted by converting numerical information into modeling, they cannot be fully verified [57]. It is also not possible to test factors that may cause clinical fatigue. For these reasons, although the FEA results give a foreseen about structural deformation behaviour, the data obtained as a result of the study should carfully be interpretted for clinical applications. In addition to the results of this study, which created 5 different clinical scenarios requiring post core restoration after crown destruction, it is inevitable that there are clinical situations that require more conservative treatment needs where root canal treatment cannot be applied due to the use of various medications that may develop osteonecrosis. At this point, it has also been reported that tissue level filling procedures after root canal treatments and endodontic restoration are a safe approach in severely damaged teeth, especially in patients taking Bisphosphonates [58]. This is one of the limitations of this study. This study can be supported by clinical in vivo studies with long-term follow-up for different crown alternatives.

5. Conclusion

This study primarily investigates how various crown alternatives affect tooth components with regard to root canal treatment, apical lesions, and fiber posts, using the Finite Element Analysis method. Different restorative treatment methods applied to root canal-treated teeth with periapical lesions can impact the stress in the alveolar bone and the biomechanical response of the tooth. High stress values in the cortical bone at the cervical line of the tooth have been noted to diminish towards the apical region. This observation suggests a potential healing effect, reducing pressure in the periapical lesion area. Composite resin restorations are deemed the preferred treatment option for restoring root canal-treated teeth with lesions. Stress values have a tendency to rise with the use of a fiber post and crown application. This situation can be mitigated by clinicians selecting the appropriate infrastructural material.

Additionally, following conclusions can be underscored.

1. Although similar deformation behavior was observed, there were differences between the stress and deformation values along the root surface with different crown materials in the FEA scenario results.
2. Crown restoration models made for RCT teeth with apical lesions had relatively higher maximum stresses, referencing the material's elastic deformation behavior capability (Model B: 80.39 MPa; Model C: 124.64 MPa; Model D: 124.46 MPa; Model E: 136.05 MPa).
3. In all models with an apical lesion (Fig. 5, Models B-E), the lesion sites were areas of low stress, along with the trabecular bone, as softer tissue absorbs the forces and does not respond as stiffly as tissues.
4. Cortical bone was more affected than trabecular bone in terms of stresses in alveolar bone. The region with the highest values was the cortical bone region in contact with the tooth cervical line. A decrease was observed in the stresses in the alveolar bone from the cervical line to the apical region.

CRediT authorship contribution statement

Ömer Kirmali: Writing – original draft, Visualization, Project administration, Investigation, Formal analysis. **Gülsah Icen:** Writing – original draft, Methodology, Data curation. **H. Kursat Celik:** Resources, Methodology, Conceptualization. **Allan E.W. Rennie:** Writing – review & editing, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used [NAME TOOL/SERVICE] in order to [REASON]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing interest

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

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