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How does endodontic access cavity design affect the biomechanics of a maxillary premolar?? a finite element analysis study

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Abstract

Background The aim of this study was to evaluate the effect of different endodontic access cavity designs on biomechanical properties of endodontically treated maxillary premolars under various static loads by finite element analysis method.

Methods Based on cone beam computed tomography data of maxillary first premolar, the models of endodontically treated teeth with traditional access cavity (TEC-I), traditional access cavity with Class-II mesio-occlusal cavity design (TEC-II), conventional access cavity (CEC), ninja access cavity (NEC), caries-driven access cavity (Cd-EC), buccal access cavity (BEC) and bucco-occlusal access cavity (BOEC). Three different static loads which were single-point vertical load (Static I), multi-point vertical load (Static II) and multi-point oblique load (Static III) were applied. The stress distribution and maximum Von Misses stress values were recorded.

Results For the enamel surface, the stress concentration was seen around the central fossa in Static I, on the marginal edge and palatal tubercle in Static II, and on the palatal cusp tip in Static III loads. For the dentin surface, the stress concentration was observed on pericervical area and buccal root surface in Static I, on all around the root surface in Static II, and on buccal and palatal root surfaces and furcation area in Static III loads. While the minimum stress distribution was detected in control group, followed by NEC and CEC designs, the maximum stress distribution was generally monitored in Cd-EC and TEC-II cavity designs.

Conclusion The increased tissue loss in maxillary premolars due to endodontic access cavity preparation meant the higher stress distribution on the tooth surface.

Keywords Endodontic access cavity, Finite element analysis, Maxillary premolar, Minimal invasive endodontic

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Introduction

Root canal treatment leads to the loss of free water within dentinal tubules, which adversely affects the biomechanical characteristics of dentin [1]. Under physiological conditions, the presence of this water, in conjunction with internal hydrostatic pressure, enables dentin to exhibit toughness and resilience under functional stress. However, dehydration following endodontic procedures compromises this property, causing dentin to behave more like a brittle material [2]. This change not only diminishes its resistance to fracture but also disrupts the even distribution of occlusal forces, concentrating stress in the cervical region and predisposing the tooth to structural failure [2, 3]. As a result, both the removal of dentin during root canal instrumentation and the extent of coronal cavity preparation plays critical roles in determining the long-term survival of endodontically treated teeth.

Among all posterior teeth, maxillary premolars are particularly vulnerable to vertical root fractures. This vulnerability stems from their slender cervical dentin and the presence of a radicular groove—especially on the palatal aspect of the buccal root—which forms a naturally concave and thin dentin zone often referred to as the "danger zone" [3–5]. To address this anatomical weakness and improve post-treatment outcomes, various minimally invasive access cavity designs have been proposed specifically for maxillary premolars [6–9]. Some of these designs suggest accessing the pulp chamber via existing carious lesions to preserve sound tooth structure [11, 12]. Depending on the location of the caries, the cavity may be placed on the proximal or buccal surfaces [10, 12, 13]. Nevertheless, biological considerations may necessitate modifications that blend conservative principles with traditional approaches. Despite these proposals, studies evaluating the biomechanical implications of such hybrid access designs remain scarce.

Although clinical and in vitro studies offer insight into how access cavity design influences fatigue resistance, standardization is often hindered by variables such as anatomical diversity, dentin thickness, aging, occlusal load variability, and lesion size [14, 15]. Finite element analysis (FEA), in contrast, provides a highly controlled environment for evaluating mechanical responses under repeatable and uniform conditions. By eliminating intra- and inter-operator variability and anatomical inconsistencies, FEA offers a reliable simulation model for investigating stress behavior in dental structures [15, 16].

Despite the fact that the fracture resistance of maxillary premolars with different access cavity designs has been widely investigated both in vitro and through finite element analysis, most studies focus on conventional and conservative cavities [7–9]. With the increasing use of magnification systems, canal orifices have become more visible during treatment, allowing access to be modified buccally or extended bucco-occlusally when needed. To the best of the authors' knowledge, no previous study has compared the fracture resistance of maxillary premolars with these updated, modified access designs. In light of these considerations, the present study aims to evaluate the biomechanical effects of different modified access cavity designs on endodontically treated maxillary premolars using finite element analysis. The null hypothesis of the study is that access cavity configuration does not influence stress distribution within the tooth structure under occlusal loading.

Materials and methods

A sound, caries-free, fully developed human maxillary first premolar was selected for this study. The tooth was scanned using cone beam computed tomography (CBCT) (ILUMA, Orthocad, 3 M Imtec, Oklahoma, USA) under standardized settings: 90 kV, 12 mA, and a voxel size of 75 ¬µm. The resulting volumetric data were used to create a 3D digital model using Rhinoceros 4.0 software (Seattle, WA, USA).

Design of access cavities

One control model (intact tooth) and seven experimental models with different endodontic access cavity designs were generated based on distinct preparation strategies (Fig. 1).

Two access cavity designs followed conventional endodontic principles. In the TEC-I (Traditional Endodontic Cavity - Class I) model, full deroofing of the pulp chamber was performed to establish straight-line access. The TEC-II model was created by modifying TEC-I, removing the mesial wall and converting the outline into a Class II cavity form.

Three cavity configurations reflected minimally invasive philosophies. The CEC (Conservative Endodontic Cavity) preserved part of the pulp chamber roof and the lingual shelf, with a conservative outline extending from the occlusal surface toward the canal orifices. In the NEC (Ninja Endodontic Cavity), the chamber was even more preserved, allowing canal identification through limited openings and oblique visualization angles. The BEC (Buccal Endodontic Cavity) featured a 2 mm diameter entry point on the buccal surface in the cervical region, centrally positioned mesiodistally and extended coronally to connect with the pulp chamber.

Two additional cavity types were modeled to reflect common clinical scenarios. In the Cd-EC (Caries-Driven Endodontic Cavity), the access outline was expanded based on simulated caries spread, maintaining at least 2 mm of dentin at the proximal edges. The BOEC (Bucco-Occlusal Endodontic Cavity) combined buccal and occlusal entry points, integrating the design principles of BEC and TEC-I.

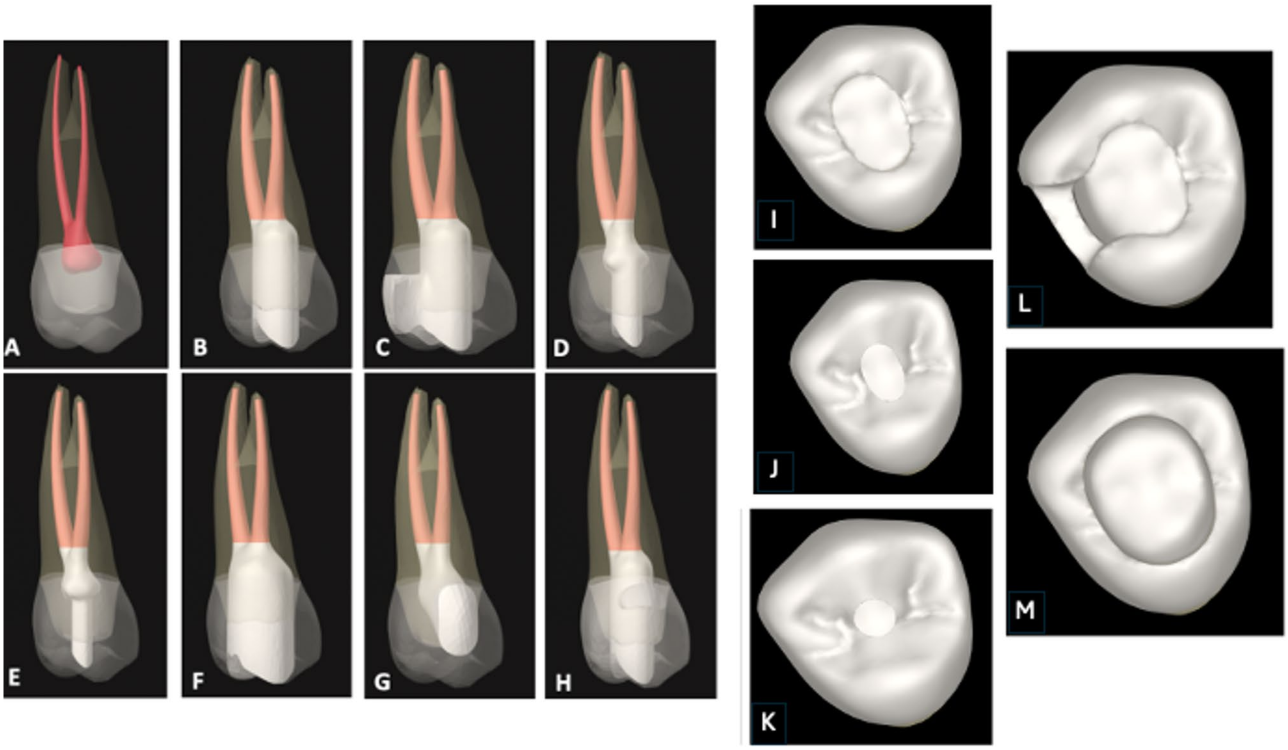

Fig. 1 Lateral "(**A**) Control, (**B**) TEC-I, (**C**) TEC-II, (**D**) CEC, (**E**) NEC, (**F**) Cd-EC, (**G**) BEC, (**H**) BOEC" and occlusal "(**I**)TEC-I, (**J**) CEC, (**K**) NEC, (**L**) TEC-II, (**M**) Cd-EC visualization of visualization of the experimental models

Endodontic simulation

Root canal simulation method was adapted from previous studies [9, 10]. To simulate the root canal preparation, a central axis was first defined within the canal space. Around this axis, a tapered canal geometry was constructed to reflect the target instrumentation dimensions. The modeled premolar had a Vertucci Type II configuration, and its apical constriction was estimated to be 0.22 mm. Accordingly, the canal was digitally prepared to represent a final shape equivalent to a #40 file with 0.04 taper, terminating 0.5 mm short of the apex. The canals were then filled with gutta-percha up to 2 mm below the orifice level. Subsequently, a flowable composite was modeled over the orifices, and the remainder of the cavity was restored using composite resin.

Modeling of supporting structures

Periodontal and alveolar structures were reconstructed digitally. The periodontal ligament, lamina dura, and cortical bone were assigned standardized thicknesses of 0.2 mm, 0.3 mm, and 2 mm, respectively. The cementum was modeled with a tapered profile: 0.175 mm in the apical third and 0.038 mm in the coronal third. A surrounding 15 mm cube of cortical bone was positioned with its upper margin located 1.5 mm apical to the cementoenamel junction.

Finite element analysis and loading protocols

All geometric models were transferred from VRMesh software into Algor Fempro for meshing and finite element simulation.

Assumptions used for modeling included:

- All materials were defined as isotropic, linearly elastic, and homogeneous.
- Ideal adhesion was assumed at all interfaces.
- The baseline tooth structure was considered free of defects.

Each model contained a unique mesh density and node count (detailed in Table 1). Mechanical properties such as Young's modulus and Poisson's ratio for each structure were assigned based on previously published data [15–20] and listed in Table 2.

Three distinct static loading protocols were applied:

- Vertical Point Load (Static I): A 250 N force applied vertically at the central fossa.
- Multi-Point Vertical Load (Static II): A cumulative 800 N force applied at four occlusal locations-buccal cusp, central fossa, and both marginal ridges (200 N each)-to replicate centric occlusion.
- Oblique Load (Static III): A 225 N load applied at a 45¬∞ angle to the long axis of the tooth, targeting

Table 1 The number of nodes and elements of models

Number		Control	TEC-I	TEC-II	CEC	NEC	Cd-EC	BEC	BOEC
Static I	Node	28,147	31,955	25,871	32,389	36,793	27,191	37,420	41,631
	Elements	143,669	135,479	113,047	152,306	154,574	118,247	156,490	164,833
Static II	Node	28,147	31,955	25,871	32,389	36,793	27,191	37,420	41,631
	Elements	143,669	135,479	113,040	152,313	154,560	118,238	156,491	164,833
Static III	Node	28,147	31,955	25,871	32,389	36,793	27,191	37,420	41,631
	Elements	143,669	135,476	113,040	152,304	154,574	118,238	156,490	164,833

Table 2 The mechanical characteristic of investigated material[23–28]

Materials	Elastic modulus (E; MPa)	Poisson ration (μ)
Enamel 17	84,100	0.33
Dentin 17	18,600	0.31
Periodontal Ligament 17	68.9	0.45
Gutta-percha 18	140	0.40
Cortical bone 17	13,700	0.3
Cancellous bone 22	1370	0.3
Composite resin 19	12,000	0.3
Flowable composite resin 15	5100	0.27
Cement 20	6800	0.31
Pulp 21	3	0.45

the lingual incline of the buccal cusp, mimicking functional lateral forces (Fig. 2).

Vertical loading conditions (Static I and II) were designed to replicate axial masticatory forces, while Static III simulated lateral chewing stresses. Stress distribution was analyzed by calculating the maximum von Mises and principal stresses on the enamel and dentin surfaces.

Results

The amount of composite resin used varied for each design with the volumes of 60.146 mm^3, 78.905 mm^3, 26.724 mm^3, 16.679 mm^3, 76.103 mm^3, 41.764 mm^3 and 66.941 mm^3 used for the TEC-I, TEC-II, CEC, NEC, Cd-EC, BEC and BOEC designs, respectively.

The maximum von mises (VM) stress values recorded in enamel and dentin of the tooth models are shown in Table 3.

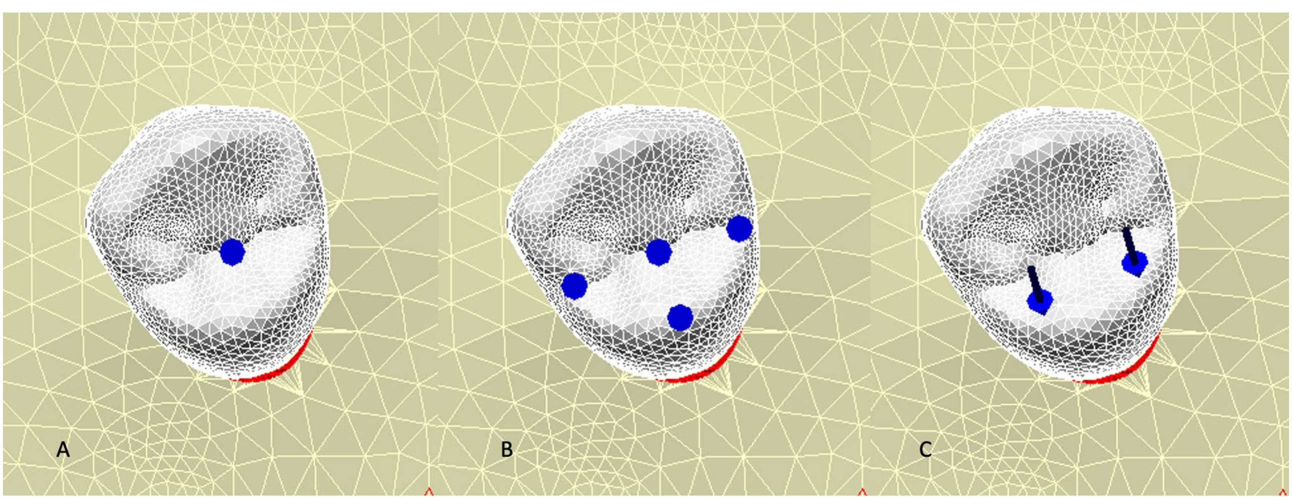

Fig. 2 Load application points observed from the occlusal view for (**A**) Static-I: single-point load, (**B**) Static-II: multi-point load, and (**C**) Static-III: multi-point oblique load

Table 3 The maximum von mises (VM) stress values recorded in enamel and dentin of experimental models

		Control	TEC-I	TEC-II	CEC	NEC	Cd-EC	BEC	BOEC
Static I	Enamel	1126.46	1334.31	15051.9	8410.95	6167.89	955.867	983.127	1333.86
	Dentin	27.4156	27.0081	47.2421	74.5601	124.921	129.772	94.8883	382.726
Static II	Enamel	2607.09	2838.2	12886.3	6763.56	4962.97	6231.26	2391.09	2141.1
	Dentin	82.1581	88.6809	93.5683	251.069	232.491	105.142	319.551	307.301
Static III	Enamel	471.723	529.303	972.368	802.136	641.031	1531.72	561.414	760.245
	Dentin	72.5174	89.2501	93.8866	104.866	97.0612	105.975	132.865	105.714

Von mises stress

Enamel

The VM stress distributions on the occlusal surface of the different cavity designs are shown in Fig. 3. The enamel stress concentration areas were characterized by force-applied points. Stress concentration was seen around the central fossa in Static I, on the marginal edge and palatal tubercle in Static II, and on the palatal cusp tip in Static III. The directing of Static II and Static III forces to the palatal cusp tip caused less stress on the buccal surface of the crown.

Under Static I load, the minimum stress concentration was observed on control group and BEC cavity design which was followed by CEC and NEC designs. The maximum stress distribution detected on Cd-EC desing along the occlusal surface including the buccal cusp tip. TEC-I and BOEC designs showed similar stress distribution on enamel surface. TEC-II design showed greater stress distribution than TEC-I, CEC and NEC designs towards the buccal cavity border and palatinal cusp.

Under Static II and III loads, the similar VM stress pattern was observed on control group, NEC and CEC designs which was lower than the other experimental groups. The maximum stress distribution was detected on Cd-EC and TEC-II designs.

Under all static load types, BOEC design showed much more stress distribution than BEC design all over the crown surface.

Dentin

Figure 4 shows the VM stress distributions on the enamel surface of experimental cavity designs. The maximum stress distribution was monitored under Static II, Static III and Static I loads, respectively. Stress concentration was seen on pericervical area and buccal root surface in Static I, on all around the root surface in Static II, and on buccal and palatal root surfaces and furcation area in Static III.

Under all static load types, the control group showed the minimum stress concentration which was followed by NEC and CEC designs. The maximum stress concentration was dominantly observed on Cd-EC design, followed by TEC-II design. In Cd-EC design, the stress was also distributed in pericervical area, which was a different pattern from the other cavity types. BOEC design showed higher stress distribution than BEC design under all static loads.

Maximum principal stress

The maximum principal stress was predominantly observed in the cervical region under Static-I loads, in both the cervical region and furcation area under Static-II loads, and on both the buccal root surface and furcation area under Static-III loads. The highest principal stress in the crown was primarily recorded around the central fossa under both Static-I and II loads. However, under Static-III loads, the maximum stress distribution shifted, predominantly affecting the buccal surfaces of the BEC, BOEC, and TEC-II cavity designs, as well as the proximal contact areas of the Cd-EC, NEC, and TEC-I cavity designs.

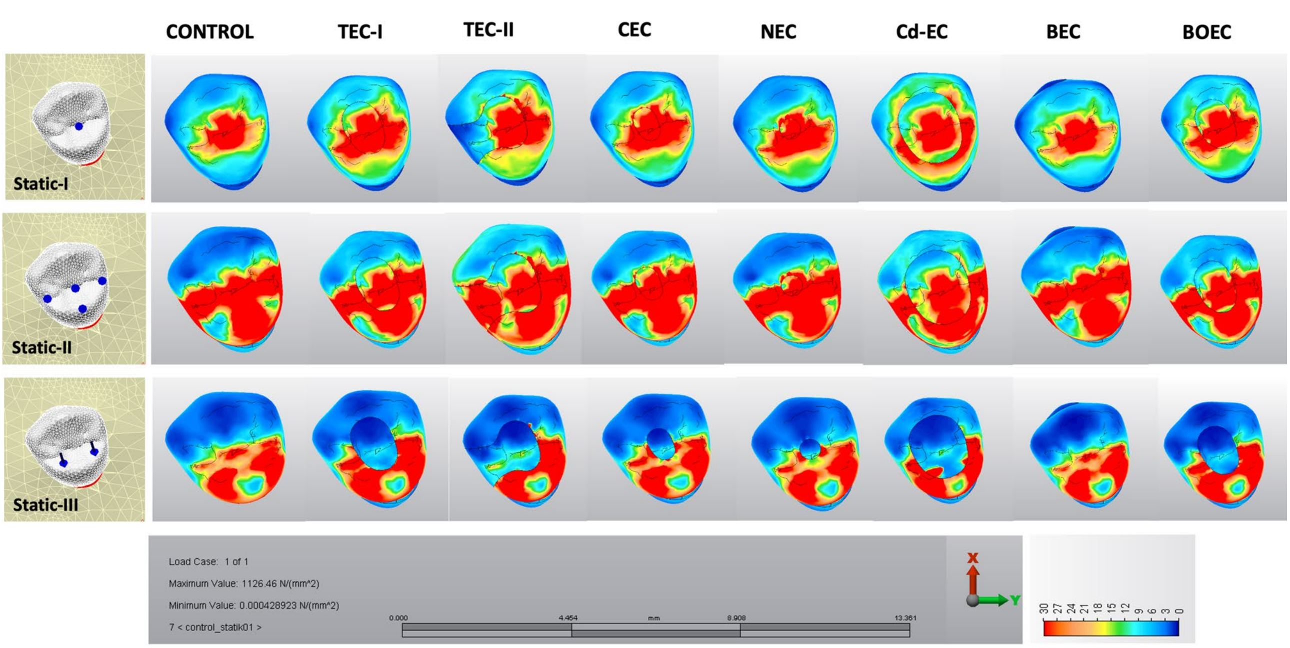

Fig. 3 Occlusal surface stress patterns of various access cavity models subjected to Static-I, Static-II, and Static-III loads

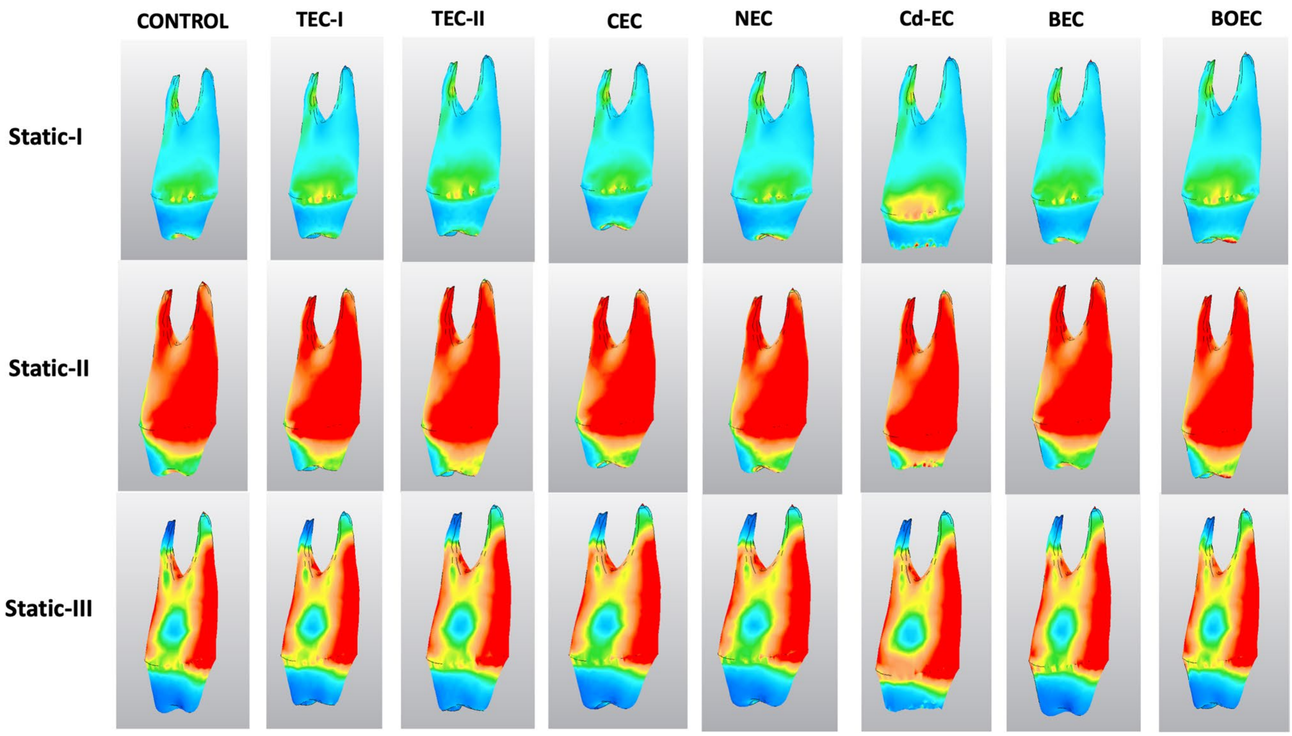

Fig. 4 Distribution of stress across the root surface

Discussion

The biomechanics of fracture in endodontically treated teeth largely rely on dentin, the primary mineralized tissue responsible for maintaining the tooth's mechanical integrity. In any situation leading to tooth fracture, the primary cause is the design of the access cavity, while the secondary factors involve the extent of root canal shaping [10, 21–23]. In the present study, different access cavities were designed compromising the biological aspects of endodontic treatment and evaluated their effect on biomechanical behavior of a maxillary premolar tooth. According to the results, the minimum stress distribution was detected in minimally invasive access cavity designs (NEC and CEC). For this reason, the null hypothesis was rejected.

The maximum stress was predominantly observed in the Cd-EC and TEC-II cavity designs. This suggests that thin proximal walls or the loss of these walls can negatively impact the stress distribution within the tooth. Abdelfattah et al. reported that the loss of a proximal wall in an endodontically treated tooth can reduce the tooth's expected lifespan by approximately 6% [10]. When the loss of proximal walls increases from one to two, the recorded stress has been shown to be nearly 1.5 times higher [10]. Correspondingly, BOEC design showed higher stress distribution than BEC design under all static loads. These results align with previous studies, indicating that as the amount of lost tissue increases, both the pattern and magnitude of stress on the tooth change [17, 25].

According to the findings of the study, stress accumulation in the enamel was predominantly concentrated on the palatal cusp, whereas in dentin, it extended toward the root surface and the pericervical area. The palatal cusp of maxillary premolar teeth, as the functional cusp, plays a major role in the chewing process, making it more susceptible to fracture This increased vulnerability is primarily due to its smaller size and thinner enamel thickness compared to the nonfunctional cusps [26]. Furthermore, the high and steep inclinations of the palatal cusp increase the horizontal component of occlusal forces, leading to stress concentration [27]. These anatomical features, combined with the increased stress under occlusal loading, contribute to a higher risk of fracture which was also shown with the results of the present study.

Furthermore, in the present study, multi-point occlusal and lateral forces led to greater and more critical stress concentrations compared to single-point forces. Similarly, Özyürek et al. [28] investigated the influence of different access cavity designs on the mechanical properties of mandibular premolars using the finite element analysis (FEA) method and reported that multi-point loading resulted in stress distribution across the entire root surface. Additionally, a single-point vertical load was found to concentrate stress within the pericervical dentin across all experimental cavity designs. These findings are consistent with the results of Arıcan et al. [29], who demonstrated that single-point occlusal forces predominantly caused stress accumulation in the pericervical region of endodontically treated teeth.

Premolar teeth exhibited considerable anatomical variability in both root configuration and root canal morphology [30]. In line with this variability, Merhej et al. [31] reported that maxillary first premolars predominantly exhibited two roots with two root canals, while maxillary second premolars most commonly had a single root and more frequently exhibited two root canals than one. The three-root and three- root canal configuration was rarely observed in maxillary first premolars. Similarly, Bulut et al. [32], in a study conducted on the Turkish population, found that maxillary premolars frequently presented with two separate roots and two root canals. Considering this, a double rooted maxillary premolar was selected for the study.

In this study, three different static loads were adopted but fatigue failure was not evaluated. Although the main cause of failure of root canal-treated teeth is fatigue failure rather than acute overload [33], the first step in acquiring the basic knowledge in such experimental studies is to observe the behavior of the tooth under static loads [34]. For this purpose, FEA method was used for the present study.

In finite element analysis (FEA), stress evaluation is a primary focus, with metrics such as von Mises stress and maximum principal stress being frequently utilized. The selection of the appropriate stress criterion is informed by the material's mechanical characteristics and the underlying failure theories [16]. Among these, von Mises stress is particularly advantageous due to its scalar representation of combined tensile, compressive, and shear stresses in three dimensions (x, y, z) [35]. Its integrative nature makes it effective for pinpointing areas of stress concentration, often illustrated through a color gradient map, where warmer colors (e.g., red) indicate higher stress and cooler colors (e.g., blue) indicate lower stress [36]. In the present study, von Mises stress was employed to quantify stress levels, as it encompasses multiple stress components in a single value. From a clinical perspective, this is critical for detecting stress-prone regions in dentin, which are commonly associated with the initiation of cracks and subsequent fractures. Such stress mapping provides valuable insight into regions susceptible to structural failure, aiding in the prediction of tooth durability under various loading conditions [37].

FEA offers a reproducible and non-invasive approach for simulating the mechanical behavior of dental structures under load [16]. Its use in this study facilitated model standardization and helped eliminate variability related to operator technique and patient-specific factors. Nevertheless, material properties within the FEA simulations were assumed to be isotropic, homogeneous, and linearly elastic assumptions that do not fully reflect the complexities of biological tissues. Therefore, the findings should be interpreted with caution and corroborated through mechanical testing and in-vivo validation. Additionally, due to the inherent limitations of computerized models, individual differences in muscle forces and craniofacial morphology were not accounted for [16]. Various static loading scenarios were applied, involving both single and multipoint forces in lateral and vertical directions. However, the effects of dynamic muscle-generated forces were beyond the scope of this study. In essence, the analysis focused on the tooth's response to acute loading, without addressing fatigue-related failure mechanisms [33]. While the results contribute to understanding the biomechanical behavior of mandibular first molars under static conditions, further investigations are necessary to explore long-term and dynamic effects.

Although the mechanical resistance of maxillary premolars after access cavity preparation has been extensively studied, there remains limited discussion regarding modern, minimally invasive cavity designs enabled by advanced visualization and instrumentation technologies. The present study highlights that the extent of coronal tissue preservation plays a critical role in the biomechanical integrity of endodontically treated teeth. Among the evaluated designs, the BEC cavity demonstrated superior fracture resistance compared to the BOEC approach, while both NEC and CEC designs outperformed traditional and caries-driven cavities. These findings underscore the clinical relevance of adopting conservative access strategies, as they may contribute significantly to the long-term structural durability of treated premolars.

Conclusion

Within the limitations of this finite element analysis study, it can be concluded that the extent and design of endodontic access cavities significantly influence the biomechanical behavior of maxillary premolars. Conservative approaches such as the ninja access cavity and conventional endodontic cavity designs were associated with more favorable stress distributions, while greater tissue loss, as observed in caries-driven and extended cavity designs, led to markedly higher stress concentrations, particularly under complex loading conditions. These findings highlight the critical importance of preserving tooth structure during access cavity preparation to enhance the mechanical resilience of endodontically treated teeth and reduce the risk of fracture under functional forces.

Abbreviations

(TEC-I) Traditional access cavity
(TEC-II) Traditional access cavity with Class-II mesio-occlusal cavity design

(CEC) Conventional access cavity
(NEC) Ninja access cavity
(Cd-EC) Caries-driven access cavity
(BEC) Buccal access cavity
(BOEC) Bucco-occlusal access cavity

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Authors' contributions
All authors have contributed significanlty, and are in agreement with the manuscript. B.A.: investigation, Methodology, writing, review and edit, supervision; G.U.: laboratory procedures, methodology, resources, funding, writing – review and edit; M.G.: laboratory procedures, methodology, resources; T.Ö.: investigation; methodology, review and edit, supervision.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was conducted in strict compliance with the ethical principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the institutional review board (Ethic committee of Istanbul Medipol University Approval no: 2019/642) and written informed consent was obtained from the patient for the use of the extracted tooth in this study.

Consent for publication
Non applicable.

Competing interests
The authors declare no competing interests.

Conflict of interest
None.

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