BASIC RESEARCH – TECHNOLOGY

Effect of Different Endodontic Access Cavity Designs in Combination with WaveOne Gold and TruNatomy on the Fracture Resistance of Mandibular First Molars: A Nonlinear Finite Element Analysis

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ABSTRACT

Introduction: This study evaluated the effect of traditional and conservative endodontic access cavity designs in combination with WaveOne Gold and TruNatomy instrumentation systems on the fracture resistance of mandibular first molars by means of nonlinear finite element analysis (FEA). **Methods:** Micro-CT images of 4 human mandibular first molars were used to generate representative FEA models. The mandibular first molars samples were scanned before and after endodontic access cavity preparation and instrumentation of all 3 canals. Five nonlinear static loads were applied vertically and horizontally to specific contact points on the occlusal surface of the teeth. Maximum von Mises stress before failure and distribution of von Mises strains were recorded and compared between groups. **Results:** Molars with conservative endodontic access cavities required similar levels of loads to reach failure compared with their control samples, whereas molars with traditional endodontic access cavities required significantly reduced loads in order to fail. According to the numerical investigation, the type of instrumentation system was found to have an insignificant effect on the fracture resistance of the teeth under study. Von Mises stress was concentrated around the cervical region and in the larger distal roots for all numerical models. **Conclusions:** The fracture resistance of mandibular first molars is influenced significantly by a reduction in dental hard tissue, which was found to control the level of the ultimate failure load for each tooth. *(J Endod 2023;49:559–566.)*

KEY WORDS

Access cavity; conservative endodontic access; nonlinear finite element analysis; traditional endodontic access; TruNatomy; WaveOne Gold

SIGNIFICANCE

Conservative endodontic access cavity preparation reduces the overall stress concentration and increases the fracture resistance. The preservation of dental hard tissue should be considered in increasing resistance to fracture during endodontic treatment.

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When evaluating longevity and retention of endodontically treated teeth, fracture and subsequent loss after endodontic treatment remain a major concern[1,2]. Preserving structural integrity and specifically pericervical dentin is a key factor influencing fracture resistance and longevity of these teeth[3,4]. Access cavity preparation and canal instrumentation are therefore aimed at preserving tooth structure as much as possible without compromising visibility and access.

Some studies highlight the importance of preserving dental hard tissue[5-7], and others report opposite results[8-12]. The reduction of fracture resistance has also been reported to be associated more with the loss of a marginal ridge or cusp rather than the design of the endodontic access cavity[11]. Research also seems to suggest no significant difference between conservative and ultraconservative access cavity designs in their effect on fracture resistance[9,13,14]. In this study, only traditional and conservative access cavity designs were evaluated.

A minimally invasive approach during endodontic access cavity and canal preparation is aimed at preserving dentin, specifically pericervical dentin[6,7]. There is sufficient research validating the use of conservative access cavities in an attempt to preserve the structural integrity and longevity of endodontically treated teeth, but little evidence exists on the role pericervical dentin and its preservation play in the fracture resistance of endodontically treated teeth[6,7,15-17].

Traditional access cavities (TAC) are prepared by deroofing the entire pulp chamber to obtain straight-line access to the coronal and middle thirds of the canal. Canal orifices should be visible without the need to change angulation[18]. Conservative access cavity (CAC) aims at dentin preservation and partial deroofing of the pulp roof to locate canal orifices without necessarily achieving straight-line access. Canal orifices are located by accessing the pulpal chamber from the central fossa in such a manner that dentin is preserved as far as possible. Access cavity walls can be either slightly convergent or divergent[19,20].

Advances in endodontics such as magnification and increased flexibility of endodontic instrumentation systems have diminished the need for TAC preparation in certain cases. Minimally invasive preparation and dentin preservation should be considered, taking the possible increased risk of instrument separation into account[21]. However, these CAC preparations might also affect the cleaning, shaping, and obturation of canals and increase the risk of iatrogenic complications during endodontic procedures[18]. A recent study by Vorster et al[22] showed greater preparation time when using WaveOne Gold (Dentsply Sirona, Ballaigues, Switzerland) and TruNatomy (Dentsply Sirona) in combination with CAC than when using TAC designs.

The WaveOne Gold reciprocating preparation system with its unique parallelogram-shaped cross section is a popular file cutting in a counterclockwise motion. WaveOne Gold files are designed with a progressively decreasing taper to preserve coronal dentin[23]. The TruNatomy instrumentation system, which is intended to aid in minimally invasive endodontic preparation, is used in rotation motion. The instruments are manufactured using a smaller initial wire blank (0.8-mm diameter) than the 1.1-mm diameter of similar instruments. The post-grinding thermal treatments further result in a product with increased flexibility[24].

Finite element analysis (FEA) is an accurate, noninvasive method used to predict the fracture resistance and the effect of different access cavity designs and instrumentation systems on the biomechanical properties of different biological material[25]. The objective of this study was to investigate the effect of different access cavity designs and instrumentation systems on the fracture resistance of endodontically treated first mandibular molars. TruNatomy is marketed as a minimally invasive preparation system, preserving pericervical dentin and ultimately aiming to increase the fracture resistance of endodontically treated teeth. A study by Vorster et al[26] reported less pericervical dentin (volume) loss during preparation with TruNatomy compared with that of WaveOne Gold. This can be explained by the difference in taper design between these 2 instruments. WaveOne Gold Primary (25/07) will result in a larger final preparation size compared with TruNatomy Prime (26/04). In this current study the authors investigated whether these findings translated to an increase in fracture resistance because conflicting results on the preservation of specifically pericervical dentin in mandibular molars and its role in fracture resistance exist in literature. The null hypothesis was that fracture resistance is not influenced by the endodontic access design or preparation system.

METHODS AND MATERIALS

Ethics approval (reference 484/2020) was obtained from the Research Ethics Committee, Faulty of Health Science, University of Pretoria before the study commenced. Four extracted human, permanent mandibular first molars meeting strict inclusion requirements were selected to ensure sample standardization. Teeth had to be intact, caries-free, unrestored with minimal wear facets, without cracks or resorption, previously untreated, with only 3 canals in the root canal system (mesiobuccal, mesiolingual, and one distal canal) clearly visible on pre-preparation radiographs. Reason for extraction was mainly due to periodontal disease or orthodontic reasons. Only first mandibular molars with similar dentin volumes (between 620 and 640 mm^3) and mesiobuccal root canals with moderate canal curvatures between 25° and 35° and radii <10 mm were selected to standardize samples[27]. To simulate clinical scenarios and for standardization, specimens were mounted in an FKG vise (FKG Dentaire, La Chaux-de-Fonds, Switzerland). Access cavity preparation was performed with an Endo-Access bur (Dentsply Sirona) and refined with an EndoZ bur (Dentsply Sirona) in the TAC design samples, using a Dental Operating Microscope (Zumax Medical Co Ltd, Jiangsu, China). TAC (Fig. 1*A*) and CAC (Fig. 1*B*) design principles were used to prepare the endodontic access cavities. Working length was determined by subtracting 0.5 mm from the length of the canal measured to the major apical terminus under ×10 magnification after exploring and negotiating canals to patency using size 8 K-Flex file (Kerr, Romulus, MI).

WaveOne Gold Primary Samples (in Combination with Both TAC and CAC)

After access cavity preparation, a pre-curved stainless steel size 10 K-file was negotiated to working length, after which the WaveOne Gold Glider (Dentsply Sirona) was used to enlarge each canal in this sample. Final preparation was done with the Primary WaveOne Gold (Dentsply Sirona) instrument.

TruNatomy Prime Sample (in Combination with Both TAC and CAC)

After access cavity preparation, a pre-curved stainless steel size 10 K-file was negotiated to working length after which the TruNatomy Orifice Modifier (Dentsply Sirona) and Glider (Dentsply Sirona) were used to enlarge each canal in this sample. Final preparation was done with the TruNatomy Prime (Dentsply Sirona) instrument.

Canal Preparation

Glide path and final canal preparation of all 3 canals of the root canal system were

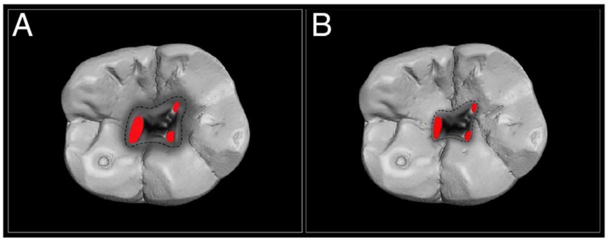

FIGURE 1 – Traditional access cavity (*A*) and conservative access cavity (*B*) preparation from occlusal view.

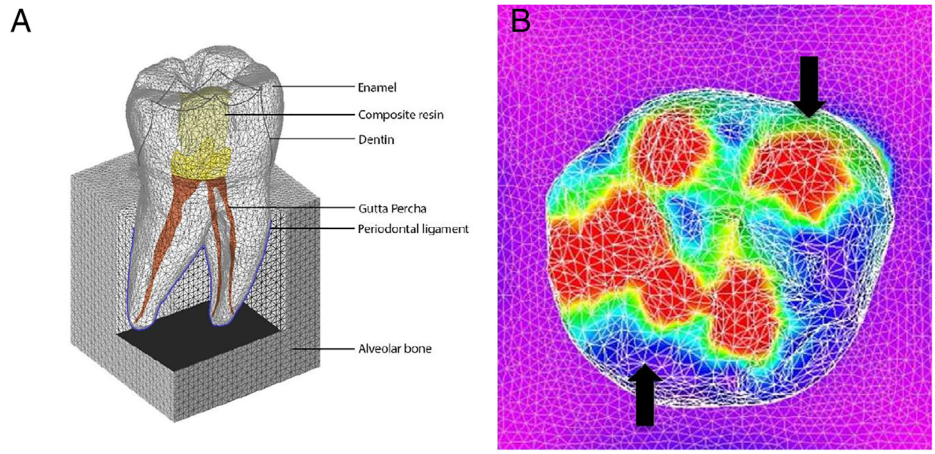

FIGURE 2 – Representative sample (*A*) 3D constructed model and (*B*) model, with *red areas* indicating the distribution of vertically applied forces and *arrows* indicating horizontal forces. Occlusal view (xy).

performed by a single experienced operator in strict accordance with the manufacturer's recommendations for each system and only used once. The WaveOne Gold Glider and WaveOne Gold Primary instrument were used in reciprocating motion (150° counterclockwise and 30° clockwise), completing 360° in 3 cycles. The TruNatomy Orifice Modifier, Glider, and TruNatomy Prime were used in rotation motion at 500 rpm and 1.5 Ncm torque. Files were allowed to progress apically on activation, using 3 easy amplitudes in a pass until working length was reached. Instruments were removed and cleaned for another 3-amplitude pass if deemed necessary until working length was reached. Preparation was confirmed by satisfactory fit of corresponding master gutta-percha cones.

Geometry Acquisitions and FEA

The 4 teeth were scanned using the XTH 225 ST (Nikon Metrology, Leuven, Belgium) micro-focus x-ray computed tomography (CT) system with a spatial resolution of 1–6 μm at the South Africa Nuclear Energy Corporation (SOC) Limited (NECSA).

Micro-CT image reconstruction was performed using VG Studio-Max visualization software (Volume Graphics GmbH, Heidelberg, Germany). These 3D models were exported as .dwg in the visualization software and imported into FEMAP (Siemens PLM Software, Plano, TX), where all surface elements generated through the scan were deleted.

Nodes were arranged in .xyz file format and imported into MeshLab (Visual Computing Laboratory, Pisa, Italy) to generate and visualize the mesh (MeshLab 3D), where the nodes were reduced manually by deleting them according to the domain of the tooth needed (enamel, dentin, gutta-percha, and composite resin). The normals were computed for the point set for each domain, after which discretization was performed using the screened Poisson method[28]. Close vertices were imported into Recap Photo (Autodesk, San Francisco, CA) to convert the .stl (Mesh) to .obj (object) file. The .obj file was then imported into MicroStation Connect Edition (Terrasolid Inc, Espoo, Finland) to perform the necessary modifications to be able to generate a solid and export it in .stp format.

A mesh was created, converted, and imported into FEMAP to obtain the representative models that were used in this research (Fig. 2*A*). The supporting alveolar bone (15-mm cube) and uniform periodontal ligament space of 0.2 mm around the roots, 1.5 mm below the cementoenamel junction, were also discretized within FEMAP, which formed the support domain of the tooth because it was not included in the CT scan. The final mesh of each tooth was discretized with tetrahedral finite elements by implementing the automatic mesh tool in FEMAP software. Modifications were made to simulate the gutta-percha obturation and a final restoration of access cavities with a composite resin material, a process that led to 8 numerical models. The anatomy of final restorations was designed to replicate possible realistic clinical scenarios as nearly as possible. The number of finite elements recorded in each numerical model ranged between 266,654 and 377,936, whereas the corresponding numbers of nodes ranged between 48,973 and 67,293[7].

On the basis of the numerical analysis performed, FEA was based on the assumptions that each material was homogenous, isotropic with nonlinear behavior, while between all components a perfect bond model was adopted. Material properties are summarized in Table 1[29-36].

Vertical and horizontal loads were applied on the tooth where contact would occur during loading conditions, which was based on their unique geometry and identifying wear facets on extracted teeth (Fig. 2*B*). This was done to replicate oral conditions that the tooth was exposed to *in vivo* as closely as possible. A vertical load of 0.15 kN was applied at 5 points in close proximity to simulate one contact point. A total of 5 contact points in the vertical direction were used for the analysis, where a horizontal load of 0.3 kN was applied at 2 points in close proximity to simulate one contact point that models the load developed at a specific concentrated area of the tooth when in mastication function. The 2 horizontal loads were applied on opposite sides of the tooth (buccal and lingual), simulating in this way the development of tension along the structure of the tooth. These loads were combined with the 5 vertical loads applied on the tooth's surface to model a realistic response and load generation at the surface of each tooth. Using the full Newton-Raphson solution nonlinear algorithm, the horizontal and vertical loads were applied in relatively small load increments until structural failure of the tooth occurred. These failure loads were tabulated (Table 2), and the stress at these ultimate load increments was recorded according to the nonlinear analyses and the respective failure load (Fig. 3).

It is important to note that the solution algorithm incorporated in NX Nastran (Siemens) foresaw the use of multiple iterations and the adjustment of the load increment according to the material nonlinearities that

TABLE 1 - Material Properties of the Different Investigated Materials

	Dentin	Enamel	Resin	Bone	PDL	GP	Pulp
Poisson	0.31	0.33	0.30	0.30	0.45	0.45	0.45
Modulus (GPa)	18.6029[29,30]	84.10[29,30]	7.00[30]	13.70[29,30]	0.069[31,32]	0.14[32,33]	0.002[34]
Tensile strength (GPa)	0.1055[35,36]	0.0115[35,36]					
Compressive strength (GPa)	0.384[35,36]	0.297[35,36]					

GP, gutta-percha; PDL, periodontal ligament.

occurred during the solution. Furthermore, it was assumed that when a material point reached its ultimate strength, the stiffness at that point was set to 0. It was deemed realistic to assume that the behavior of the materials used foresaw that their behavior was elastic until the ultimate stress level was reached. The tooth sample before access preparation and instrumentation in each sample was used as the basis of comparison in terms of quantifying the efficiency of each intervention. The failure criterion that was selected was the von Mises, whereas when yielding was reached, the strength was set to 0. This interprets that the material had no ductility. The rationale behind this approach from a numerical analysis point of view was to avoid the use of a numerically unstable and computationally demanding method such as X-FEM. Therefore, the pushover nonlinear analysis used in this study foresaw the use of a less numerically unstable material model that did not introduce discontinuities within the mesh, where the material properties were assigned in such a manner that the post-yielding mechanical behavior of a material point did not retain any remaining strength. Forces were applied on the instrumented teeth, and the reduction (percentage) in terms of ultimate failure load was reported and compared across the different samples.

RESULTS

Table 2 indicates the predicted ultimate failure loads (kg) and corresponding percentage load decrease of each representative sample. A significantly reduced ultimate capacity for failure after endodontic treatment was noted in the TAC groups compared with the CAC derived from the numerical investigation. On the other hand, no significant difference in the reduction of failure load was observed between the 2 instrumentation systems within the traditional and contracted endodontic access cavity design groups. When evaluating the numerically obtained von Mises stresses and strains (Fig. 3), it was found that nonlinearities, thus cracks, were concentrated largely at the surface of the tooth where the enamel domain is found because of the direct application of the loads and the tensile deformation of the teeth that are attributed to the horizontal loads. Von Mises stress distribution was largely concentrated around the cervical region and did not propagate into the root.

DISCUSSION

The preservation of dentin, specifically pericervical dentin, remains a controversial topic when investigating the effect on fracture resistance, with conflicting results. In this study FEA was used to simulate and evaluate fracture resistance in CAC and TAC designs. WaveOne Gold and TruNatomy preparation instrumentation systems were also compared to evaluate their effect, in combination with different endodontic access cavity designs, on the possible fracture resistance of endodontically treated mandibular first molars. TruNatomy is marketed as a minimally invasive endodontic preparation system, whereas WaveOne Gold is a popular single-file reciprocating system. Four representative samples were evaluated to see the effect of dentin preservation on fracture resistance, with the unprepared tooth in each sample acting as a control. Groups prepared with minimally invasive CAC designs required almost identical loads after endodontic treatment to induce failure compared with the corresponding control tooth. In the group where traditional methods were used to prepare the access cavity, a much reduced ultimate load was required for the sample to fail compared with the control tooth sample. It is important to note that exact figures cannot be used as an indication of a reduction in fracture resistance, because all 4 samples were anatomically different (although similar in size and root curvature); therefore, the percentage decrease in ultimate tooth capacity is a more accurate representation of possible clinical scenarios and the overall effect that the preparation has

TABLE 2 - FEA Results

	TAC/WOG		CAC/WOG		TAC/TN		CAC/TN	
	Control	Instrumented	Control	Instrumented	Control	Instrumented	Control	Instrumented
Vertical load at failure (kg)	22.27	16.41	17.58	17.19	30.47	21.60	16.41	14.84
Horizontal load at failure (kg)	17.81	13.13	14.06	13.75	24.38	17.28	13.13	11.87
Reduction in failure load due to preparation	26.32%		2.22%		29.12%		9.52%	

TN, TruNatomy; WOG, WaveOne Gold.

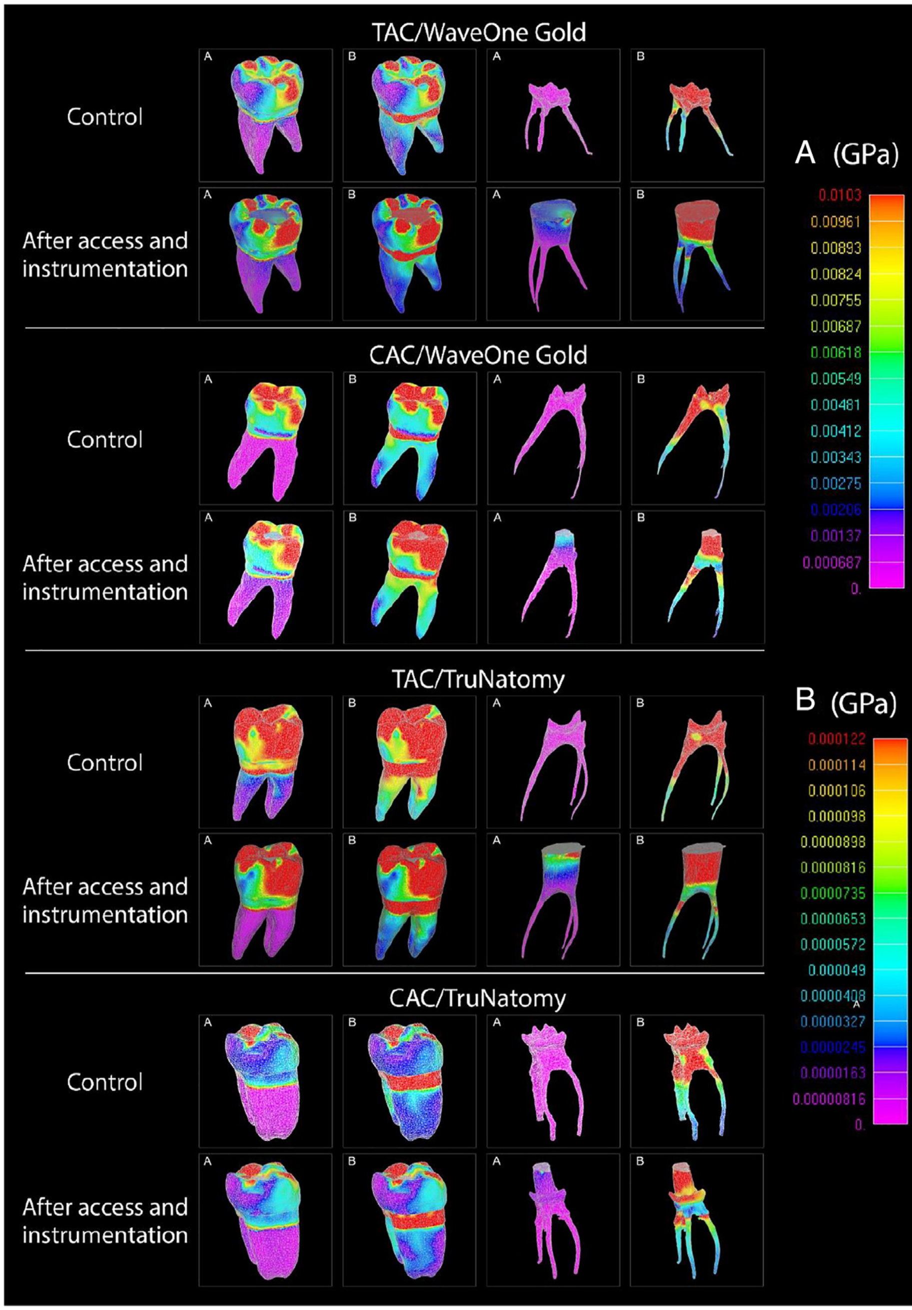

FIGURE 3 – Representative samples indicating Von Mises contours. (*A*) represents stress, and (*B*) represents strains.

on each tooth. In the parametric investigation it was also found that there was no significant difference in the reduction of the failure load between the 2 instrumentation systems. This finding could suggest that in both traditional and conservative endodontic access cavity designs the root canal instrumentation system and therefore canal taper did not influence the overall fracture resistance in this study. A study by Elkholy et al[15] also concluded that access and the removal of dental hard tissue were more instrumental in fracture resistance than canal taper. A study by Vorster et al[26] evaluating the remaining dentin thickness and volume loss of pericervical dentin after traditional and conservative access cavity preparation in combination with WaveOne Gold and TruNatomy instrumentation reported no significant difference in dentin loss within the same access cavity preparation groups. Similarly, in this study no significant difference in fracture resistance and stress distribution was reported between samples with similar access cavity designs.

The nonlinear FEA investigation revealed that the von Mises stresses were concentrated around the cervical area of the samples both before and after preparation. Strain was observed to be concentrated largely in the distal roots. This is similar to a study by Zhang et al[30], where stress concentration was also observed around the larger palatal root in maxillary first molars. In addition, stress contours and crack formation within enamel presented in Figure 3 were similar to those described by Zhang et al[30]. Cracks propagated in a mesiodistal plane following the central fossa.

By investigating the mechanical response of the composite resin, it was found that in all 4 prepared models the material did not develop any damage because of the relatively low stress level development. This mechanical response phenomenon is attributed to the fact that the composite resin is more than 10 times more flexible than the enamel and develops similar strains to those in the enamel during the nonlinear analysis. This leads to the lower stress development within the composite resin material, which can be easily determined using Hooke's law. Furthermore, it was found that the enamel and the stiffer exterior material of the tooth act as a shell for the encapsulated dentin and gutta-percha domains, leading to a failure of the enamel and then the failure of the other materials. This mechanical response was expected; it is the classical mechanical response of a structure that consists of materials of different hardness and strength, where the strongest and stiffest material is on the exterior and the more flexible and weaker materials are found toward the core. For this reason and because the strain development is continuous for all materials of the tooth, the material with the largest Young modulus (in this case the enamel) develops the largest stresses for the same strain development. Because the composite resin is designed to have a higher ultimate stress than the enamel, it is evident that the enamel will always fail first at the same strain levels, whereas because debonding between the enamel and composite resin was not considered in these numerical models, the numerical failure is expected to occur at the surface of the enamel.

The support of the teeth by the human bone was found to be sufficient because it never failed for the applied loads, forming a sufficient foundation to the under-study teeth and their roots. The root canal system and gutta-percha obturation material do not control the failure type, and this is attributed to the fact that the loads are applied at the surface of each tooth. This is composed of enamel, the stiffest material component of the structure. Because the stiffer enamel receives the load from human mastication directly, it fails first, leading to the termination of the nonlinear analysis due to numerical instabilities. Numerical instabilities are caused by an ill-conditioned stiffness matrix; many tetrahedral elements enter the nonlinear zone, leading to zero or negative diagonal terms in the stiffness matrix, creating singularities. If a stiffness matrix is singular, it cannot be inverse, and therefore the solution cannot continue. Therefore, the physical interpretation of this numerical phenomenon is failure of the tooth structure. The numerical investigation revealed that the decrease in tooth ultimate load within the CAC groups was significantly lower than in the 2 TAC groups. This finding is consistent with other recent studies on fracture resistance in molar teeth[13,16,30].

Five static vertical and horizontal loads were applied in this study to model loads developed during a realistic mastication event. The failure of endodontically treated teeth is ostensibly caused by fatigue rather than an acute overload during mastication[37]. This is a limitation of this study, because fatigue-induced failure was not taken into consideration. However, static loading is considered an important step in obtaining the basic biomechanical behavior pattern in the response to stress loading in endodontically treated teeth during mastication. The possibility of micro-fractures during access cavity preparation and final canal instrumentation are also factors not considered in this analysis; this could be the subject of future research. In all models the highest stress concentration was seen in the cervical area.

The preservation of dentin by means of conservative treatment of endodontic access cavities might lead to increased fracture resistance. In future research, other factors such as the risk of procedural errors, transportation, and centering ability should be considered when deciding on an appropriate endodontic access cavity.

It is now evident that the null hypothesis is rejected, because within the limitations of this study it was found that the size of the access cavity and the amount of dentin and enamel sacrificed during endodontic access cavity preparation can contribute significantly to fracture resistance in mandibular first molars. The researchers also concluded that the type of instrumentation system did not play a significant role in increasing fracture resistance when comparing WaveOne Gold and TruNatomy. They would like to emphasize that only fracture resistance in mandibular molars prepared with traditional and conservative access cavities was evaluated and that many other factors should also be considered when clinicians choose the type of access cavity.

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The authors deny any conflicts of interest related to this study.

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