Original Article

The influence of dental cavity on biomechanical stress and strain distribution: A finite element analysis

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Abstract

Context: Understanding tooth biomechanics is essential for creating effective and durable dental restorations. While intact teeth are inherently resilient, cavity preparation compromises structural integrity, increasing fracture risk.

Aims: This study utilized finite element analysis (FEA), the dominant *in silico* method for biomechanical investigation, to evaluate how cavity size influences stress and strain distribution in a three-dimensional mandibular molar model derived from micro-computed tomography.

Subjects and Methods: An FEA simulation was conducted on three tooth models (intact tooth, conservative cavity, and extensive cavity) under a 565 N occlusal load. Given the nonnormally distributed data, nonparametric statistical analysis (Kruskal–Wallis and Mann–Whitney tests) was performed.

Results: The analysis revealed a direct, significant correlation between cavity size and maximum stress magnitude. The intact tooth exhibited the lowest maximum stress (96.18 MPa), which significantly increased to 165.72 MPa (conservative) and 185.32 MPa (extensive). Conversely, the maximum strain capacity was highest in the intact tooth (0.007503) and decreased in prepared teeth (0.006031 for conservative and 0.006217 for extensive), suggesting cavity preparation amplifies localized stress while reducing the tooth's overall flexibility.

Conclusion: The findings confirm that cavity size is the most crucial determinant of structural risk. A conservative approach mechanically preserves tooth function. Furthermore, the lingual cusp and the cervical area were identified as the primary mechanical weak points under functional load.

Keywords: Finite element analysis; strain distribution; stress distribution; tooth cavity; von Mises stress

INTRODUCTION

Understanding how teeth react to biting forces is crucial for designing durable dental restorations. Intact teeth offer superior strength and resilience, whereas teeth compromised by caries suffer structural damage, which reduces mechanical integrity and increases fracture risk. The biomechanics of teeth are best investigated using finite element analysis (FEA), a numerical technique effective for simulating loads and predicting potential fracture sites.[1,2] This study aims to use FEA to evaluate stress and strain distributions across three models: intact tooth, conservative cavity, and extensive cavity. The findings provide valuable insights for enhancing restoration quality and patient care.

SUBJECTS AND METHODS

This study utilized three treatment groups (intact tooth, conservative cavity, and extensive cavity) to measure stress and strain distribution. Ethics approval was obtained from the Research Ethics Commission.

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The analysis began with a micro-computed tomography (micro-CT) scan of an extracted mandibular first molar using a micro-CT scanner (Bruker MicroCT SkyScan 1173). The parameter settings for the micro-CT scanner were as follows: high resolution, a scan type of 2240 × 2240 pixels (12.8 resolution), and minimum profile line settings of 30%–50%, 130 kV, and 61 mA, yielding a digital imaging and communications in medicine dataset. Segmentation of enamel and dentin was performed (three-dimensional [3D] Slicer), saved as stereolithography file, and subsequently reduced using Meshmixer (Autodesk, Inc.) due to the computationally heavy mesh size. The model was then refined in SolidWorks 2022 (Dassault Systèmes SolidWorks Corporation) to design the base, cavity geometry, and food bolus. The study utilized Class I prepared cavities with two distinct dimensions: (1) Conservative: 2 mm height × 2 mm diameter (H2 D2), (2) Extensive: 3 mm height × 4 mm diameter (H3 D4).[3]

The bone model featured 1.5 mm cortical bone over 22 mm cancellous bone. To simplify the crown-focus analysis, the pulp and periodontal ligament (PDL) were excluded from the study. The exclusion was based on the literature, as the low stiffness of the pulp and PDL makes their influence on crown stress negligible.[4] Material properties [Table 1] were assumed to be linearly elastic, homogeneous, and isotropic. All interfaces were considered perfectly bonded, and the bone base was fully constrained.[5-8]

A grid independence test validated the model's reliability, which subsequently utilized an element mesh size of 0.3 mm.[4] An occlusal load of 565 N was applied to the mandibular molar crown.[9] A 3D FEA simulation (ANSYS 2024) was conducted with three repetitions, resulting in a total of 18 simulations. Since the data obtained was not normally distributed, a nonparametric analysis was performed using the Kruskal–Wallis test and the Mann–Whitney test.

RESULTS

Stress and strain magnitude

Finite element models were created for all conditions (intact tooth, conservative, and extensive cavity) to evaluate biomechanical performance. The maximum von Mises stress increased significantly following preparation: 96.2 MPa (intact tooth), 165.7 MPa (conservative), and 185.3 MPa (extensive). Conversely, maximum elastic strain was highest in the intact tooth (0.0075) and lower in the prepared cavities (0.0060 conservative; 0.0062 extensive). This suggests preparation alters the global strain profile while dramatically increasing localized stress.

Statistical analysis

The Kruskal–Wallis test revealed a statistically significant difference in both stress and strain distribution across the three models ($P = 0.023$). Further Mann–Whitney tests [Table 2] confirmed that the presence and type of cavity significantly affect the tooth's mechanical behaviour ($P < 0.05$).

Table 1: Mechanical properties of the material that be used in the study

Material	Elastic modulus (GPa)	Poisson's ratio	References
Enamel	84.1	0.33	[5,6]
Dentin	18.6	0.31	[5,6]
Cortical bone	13.7	0.30	[7]
Cancellous bone	1.37	0.30	[7]
Food bolus	3.41 ($\times 10^{-3}$)	0.10	[8]

Table 2: Results of the Mann–Whitney test between different types of tooth models with stress and strain distribution

Groups		Stress distribution	Strain distribution
Intact tooth (no cavity)	Tooth with a conservative cavity	0.043*	0.043*
Intact tooth (no cavity)	Tooth with an extensive cavity	0.034*	0.043*
Tooth with a conservative cavity	Tooth with an extensive cavity	0.034*	0.043*

*$P<0.05$=there is a significant difference

Group comparisons

Intact tooth versus conservative

Significant differences were found in both stress and strain distributions ($P = 0.043$). This demonstrates that even minimal removal fundamentally alters the tooth's biomechanics.

Intact tooth versus extensive

Significant differences were found in both stress ($P = 0.034$) and strain ($P = 0.043$). Extensive preparation fundamentally compromises load-bearing capacity and structural integrity.

Conservative versus extensive

Significant differences were observed in both stress ($P = 0.034$) and strain ($P = 0.043$). The structural disturbance escalated with cavity size, leading to a greater reduction in resistance to deformation.

Biomechanical observations

Figure 1 illustrates the stress riser effect, showing maximum stress shifting from the cusp tip (intact) to the internal cavity margins (prepared models), confirming the elevated stress values. Figure 2 shows that the highest values for both strain and total deformation were consistently localized to the lingual cusp region across all models, with overall structural displacement increasing proportionally with cavity size.

DISCUSSION

Comprehending how stress and strain are distributed

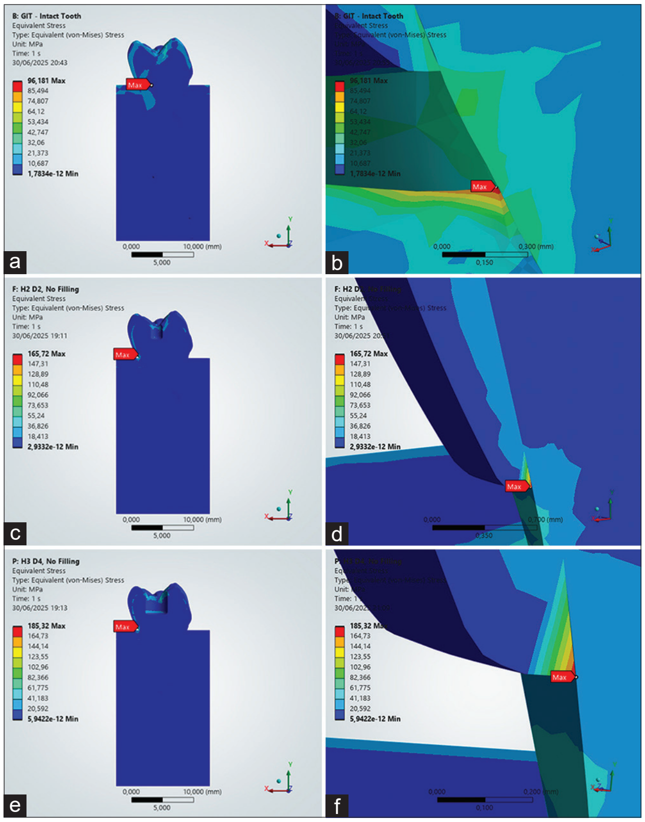

Figure 1: Overall and magnified views of von Mises stress distribution in (a and b) intact tooth, (c and d) conservative, and (e and f) extensive Class I cavity models

within teeth is crucial for restorative treatments and the design of new dental materials. The intricate mechanics of teeth under pressure are influenced by their biological structure, shape, and the materials used in restorations.

Intact teeth maintain a significant biomechanical advantage over those with cavities. Research indicates that intact teeth exhibit optimal stress distribution during functional loading, minimizing the risk of fracture.[10] In a healthy, intact tooth, the enamel and dentin form a continuous, smooth shell whose geometry results in a homogeneous stress distribution. When an occlusal load is applied, the forces are distributed over a large, curved surface area. Stress concentrations are generally located at the cusps and are smoothly dissipated through the dentin toward the root and supporting bone. This highly optimized system results in relatively low and widespread peak stresses [e.g., maximum stress of 96.2 MPa in the intact tooth model in Figure 1].

Conversely, the Mann–Whitney test results [Table 2] underscore the significant impact of cavity size on the tooth's biomechanical integrity. The presence of a cavity fundamentally alters stress and strain distributions, with the extent of the preparation playing a crucial role. Extensive cavities cause the most significant changes to the tooth's structural integrity under stress and strain.

The procedure of tooth preparation, even for dental fillings, introduces the stress riser effect. This involves removing a volume of the continuous, load-bearing structure, which creates abrupt internal corners and sharp changes in stiffness at the cavity walls. Stress lines, which normally flow smoothly through the dental tissues, must crowd and abruptly divert around this discontinuity. This crowding significantly amplifies the localized stress at the internal margins.

Consequently, the maximum stress shifts from the external cusp tips to the internal axial and gingival walls of the cavity preparation. This explains why the prepared cavity models (both conservative and extensive) show peak stresses (ranging from 165.7 MPa to 185.3 MPa) that are much higher than those observed in the intact tooth [Figure 1].

When comparing conservative versus extensive cavities, the conservative cavity (H2 D2), despite creating a stress riser, involves less material removal, leaving more surrounding intact dentin to support the remaining walls. According to González López *et al*.,[11] a smaller cavity results in thicker and stiffer dentin walls, which are better able to resist deformation (strain) and distribute stress uniformly under occlusal loads.

In an extensive cavity (H3 D4), the larger size removes a significant portion of the internal dentin, leading to wider, unsupported cusp walls. This places greater shear and tensile forces on the remaining structure. The magnitude of the peak stress at the internal margins is usually higher in the extensive cavity (approximately 185.3 MPa vs. 165.7 MPa for conservative) because the significant loss of dentin and enamel causes the remaining cusps to become more flexible. This flexing often results in cuspal deflection, which is a crucial biomechanical issue.[11] The reduction in the natural stiffness allows the cusps to strain more under the same load, leading to statistically higher stress values. High cuspal deflection is associated with insufficient residual dentin thickness overlying the pulp chamber.[12]

The stress and strain concentration areas shown in Figures 1 and 2 are closely related to mandibular first molar biomechanics. While the buccal cusp is functional, the von Mises stress is often highest at the cementoenamel junction (CEJ) on the nonfunctional (lingual) cusp. This is due to the occlusal load on the buccal cusp causing crown flexure, resulting in tensile stress on the linguo-cervical side. Dentin is highly susceptible to tensile stress, which makes the CEJ beneath the lingual cusp a major risk area.[13]

In this study, the occlusal load applied to the food bolus was distributed evenly over the bolus surface, thereby affecting the entire occlusal surface of the tooth. In this simulation, not only the buccal cusp but also the lingual cusp was subjected to the load. The presence of an occlusal load on the lingual cusp also plays a role in the formation

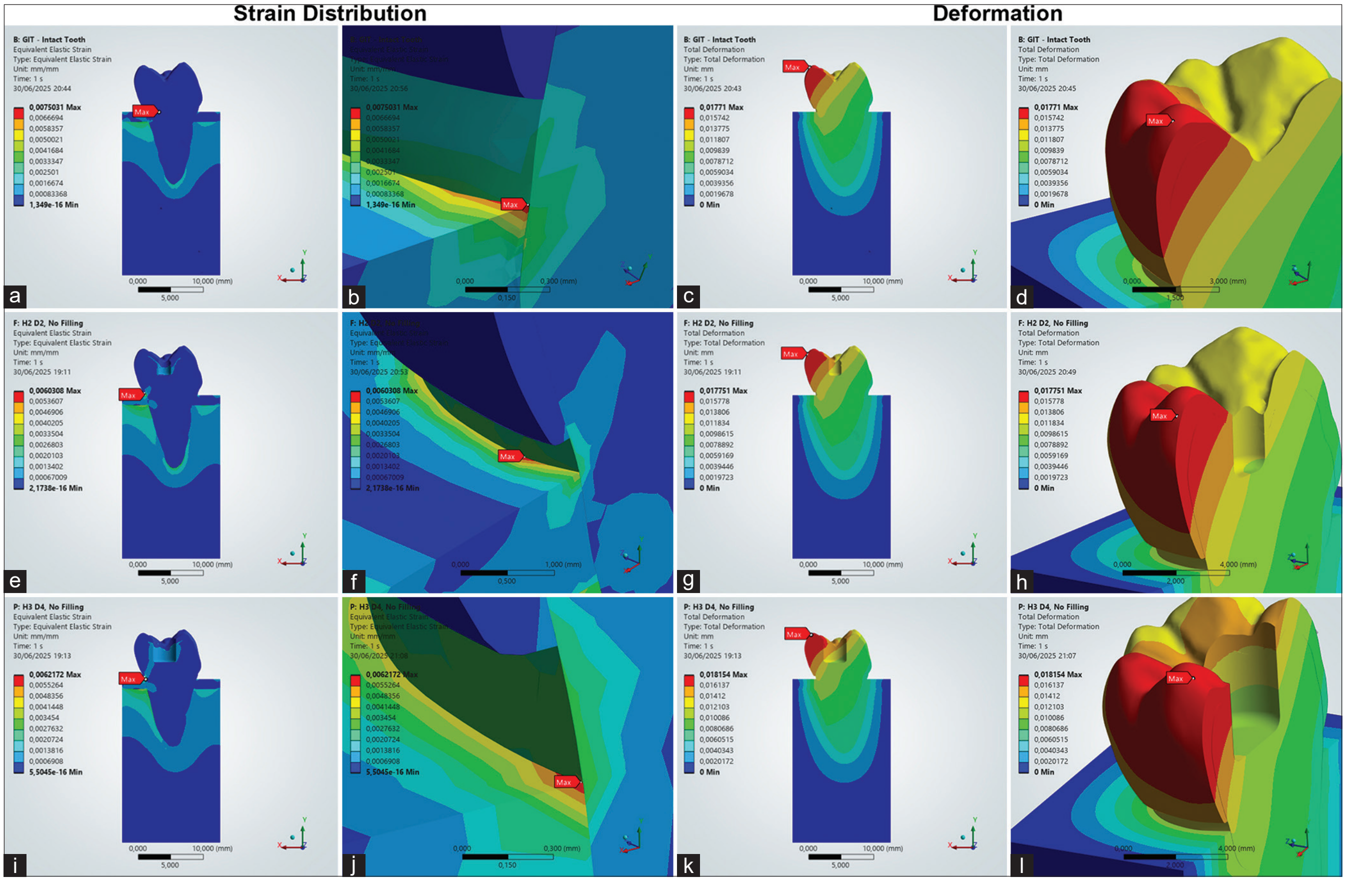

Figure 2: Overall and magnified views of strain distribution and total deformation in intact and prepared Class I dental models: (a-d) intact tooth, (e-h) conservative, and (i-l) extensive Class I cavity models

of stress concentration in the cervical area of the tooth below the lingual cusp.

Based on research by Sender and Strait,[14] occlusal force on the cusp tip induces enamel flexure, which generates tensile stress at the dentinoenamel junction. This tensile force then causes the underlying dentin to expand laterally, subsequently transferring tensile stress to the cervical margin of the tooth. This process ultimately concentrates stress in the cervical area below the loaded cusp (e.g., the lingual cusp).[14]

This mechanism is supported by findings that lingual cusp fractures occur twice as often as buccal cusp fractures. The higher fracture potential is linked to the lingual cusp's anatomy: A smaller size, lower cuspal inclination angle, and thinner enamel thickness.[13] Total deformation [Figure 2] was consistently localized to the lingual cusp in all groups, confirming its susceptibility to strain during chewing. Therefore, when restoring mandibular molars, the focus should be on protecting not only the functional (buccal) cusp but also the non-functional lingual cusp.[13]

The biological implications of a cavity cannot be overstated; caries progression affects the dentin and pulp, leading to potential necrosis and inflammation.[15] Consequently, the preparation of cavities, essential for restorative procedures, invariably compromises tooth integrity by reducing its capacity to withstand occlusal forces.[16-18] Dental professionals increasingly emphasize the importance of preserving healthy tooth structure. This principle is reflected in modern conservative dentistry practices that advocate for treatments minimizing tooth structure removal to maintain integrity, often termed minimally invasive techniques.[19,20]

In direct composite restorations, using a fiber-reinforced composite intermediate layer significantly reduces stress concentration.[21] Zirconia is favored for complex restorations as its superior stress distribution contributes significantly to enhanced structural integrity and the protection of remaining tooth tissue.[22] Furthermore, complex restorative techniques, such as post-and-core systems, introduce new zones of stress concentration that can lead to future fractures.[23,24] For endodontically treated molars, maintaining cuspal structure optimizes dental tissue integrity and contributes to superior clinical outcomes.[25]

These findings emphasize the critical importance of preserving as much tooth structure as possible during restorative procedures. The greater the amount of tooth structure removed, the more likely the tooth is to exhibit altered mechanical behaviour and increased susceptibility to failure. These results strongly suggest that a conservative approach to cavity preparation helps maintain the tooth's original biomechanical properties, ultimately improving its long-term prognosis.

CONCLUSION

The results obtained from the FEA simulations lead to the following key conclusions regarding the biomechanical integrity of the different cavity models:

1. Cavity size determines structural risk: Cavity preparation severely compromises tooth integrity, with the extensive cavity causing the greatest stress riser effect and the highest maximum von Mises stress, significantly exceeding the stress observed in the intact tooth
2. Conservative approach preserves function: A conservative cavity preparation is essential to minimize stress amplification and maintain structural resilience
3. Lingual cusp is the mechanical weak point: The FEA consistently identified the linguo-cervical region as the area of maximum stress and total deformation in all models, suggesting the nonfunctional lingual cusp and its supporting structure are the most critical anatomical failure points under occlusal loading.

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Conflicts of interest

There are no conflicts of interest.

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