Received: 27 October 2023 | Revised: 27 February 2024 | Accepted: 10 March 2024

DOI: 10.1111/ipd.13183

INTERNATIONAL JOURNAL OF PAEDIATRIC DENTISTRY WILEY

ORIGINAL ARTICLE

Evaluation of the effect on the permanent tooth germ and the adjacent teeth by finite element impact analysis in the traumatized primary tooth

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Abstract

Background: One of the primary concerns in the paediatric emergencies is traumatic dental injuries.

Objective: This study aimed to create trauma in primary teeth and reveal its effects finite element analysis.

Design: Three-dimensional models were created using cone-beam computed tomography images, representing a maxillary primary central incisor. An impact force moving at a speed of 10 m/s was simulated on the labial tooth surface in two directions: buccal and incisal.

Results: The stress and deformation experienced in the adjacent tooth due to the primary tooth were higher than those generated in the permanent tooth. Forces applied in the incisal direction resulted in higher levels of stress and deformation in the permanent tooth germ. The difference between the stress and deformation values in primary teeth in the forces applied in the buccal and incisal directions is 21% and 75%, respectively; in the permanent tooth germ, this difference was 233% and 100%, respectively.

Conclusions: Based on the findings of this study, it is crucial to thoroughly evaluate not only the affected primary tooth but also the adjacent teeth and the permanent tooth germ in traumatic dental injuries. This comprehensive examination allows for the anticipation and management of potential long-term problems.

KEYWORDS

deformation, finite element method, permanent tooth germ, primary teeth, stress, traumatic dental injury

1 | INTRODUCTION

Dental injuries are commonly encountered in urgent situations, particularly in early childhood.[1] It has been reported that the maxillary central teeth are mostly affected in primary tooth injuries.[2] In traumatic dental injuries, the affected primary tooth, the surrounding tissues, the adjacent teeth, and the permanent tooth germ are involved within the traumatic impact area. It has been reported that complications may develop after a few weeks or months, even if the pulp response is positive after trauma.[3]

Complications may occur in the permanent dentition because of traumatic injuries in the primary dentition period. In this process, incoming traumatic forces are transmitted to permanent teeth, as the apex of the primary tooth exhibits close anatomical proximity to the permanent tooth germ.[4] Trauma to the oral region due to the proximity between the roots of the primary incisors and the permanent tooth germs may result in possible damage to the developing teeth.[5]

The studies have stated that the most important factor causing developmental disorders is the type of primary tooth trauma, regardless of the developmental stage of the permanent tooth germ at the time of trauma.[6] A significant relationship was found between the prevalence and severity of developmental disorders in permanent teeth after intrusive luxation and avulsion injuries in primary teeth.[6,7]

As far as we know, the forces come from different directions to the primary tooth; no studies co-test how they affect stresses and deformations in both the adjacent primary teeth and the permanent tooth germ. It is challenging and ethically problematic to determine and demonstrate the precise impact of traumatic events on teeth and surrounding tissues through experimental studies. The finite element method (FEM) analysis, however, allows for the simulation of these events on patient-specific models. This approach enables the evaluation of stress and deformation values resulting from applying specific forces to the teeth at defined time intervals.[3,5,8] The analysis of a physically determined problem is based on the FEM; it is expressed as a numerical application in which the problem is modeled and solved in a virtual environment with computer support.[9,10]

This study aimed to evaluate the stresses and deformations in the teeth adjacent to a maxillary primary incisor that has been impacted by forces from different directions using a FEM and determine the stress and deformation distributions of these forces in the permanent tooth germ and the adjacent teeth. The null hypothesis tested was that the stresses and deformation generated during an impact will not affect the adjacent teeth and the permanent tooth germ, and the stresses and deformations produced by the impact will not be affected by the direction of the impact.

Why this paper is important to paediatric dentists

- In our study, areas of stress and deformation were observed not only in the primary tooth to which trauma force was applied but also in the adjacent tissues and the permanent tooth germ.
- The study's findings revealed that the stresses and deformations in primary teeth were higher than those in the permanent tooth germs.
- Impact on the incisal edge caused higher stresses and deformations compared with buccal impact.

2 | MATERIALS AND METHODS

2.1 | Ethics approval

This study was approved by the Non-Invasive Ethics Committee of Recep Tayyip Erdogan University Faculty of Medicine (approval number: 2023/133). A consent form was obtained from the child patient and his parents whose radiographic images were used.

2.2 | Geometry

Cone-beam computed tomography (CBCT) images of a 5.5-year-old boy with similar occlusal features to other children with normal occlusion were used to generate geometric cross-sections. To obtain the solid model correctly, CBCT (NewTom VGI evo [Quantitative Radiology, Verona, Italy] with the following parameters: 200 μm voxel size, 110 Kvp, 3 mA, and 1.8 s) images of the case were transferred to the Mimics Innovation Suite 24.0 (Materialise NV, Leuven, Belgium) software. This process is especially important in modeling every detail of the maxillary structure by the original. Thanks to the Mimics Innovation Suite 24.0 medical imaging software, the solid model of the teeth, soft tissue, and bone structure of the case were cleaned separately for each structure (compact bone, cancellous bone, enamel, and dentin) using 3-Matic16.0 and segmented with the help of image intensities. The 3D model of the created maxillary structure is given in Figure 1A,B.

After the final segmentation of the model was made using the Solidworks program for the different structures of the obtained dental solid model, the model created was ready for structural analysis. Several popular numbers of software are widely used to implement FEM solutions. Finite element analysis (FEA) of the physical problem (stress and

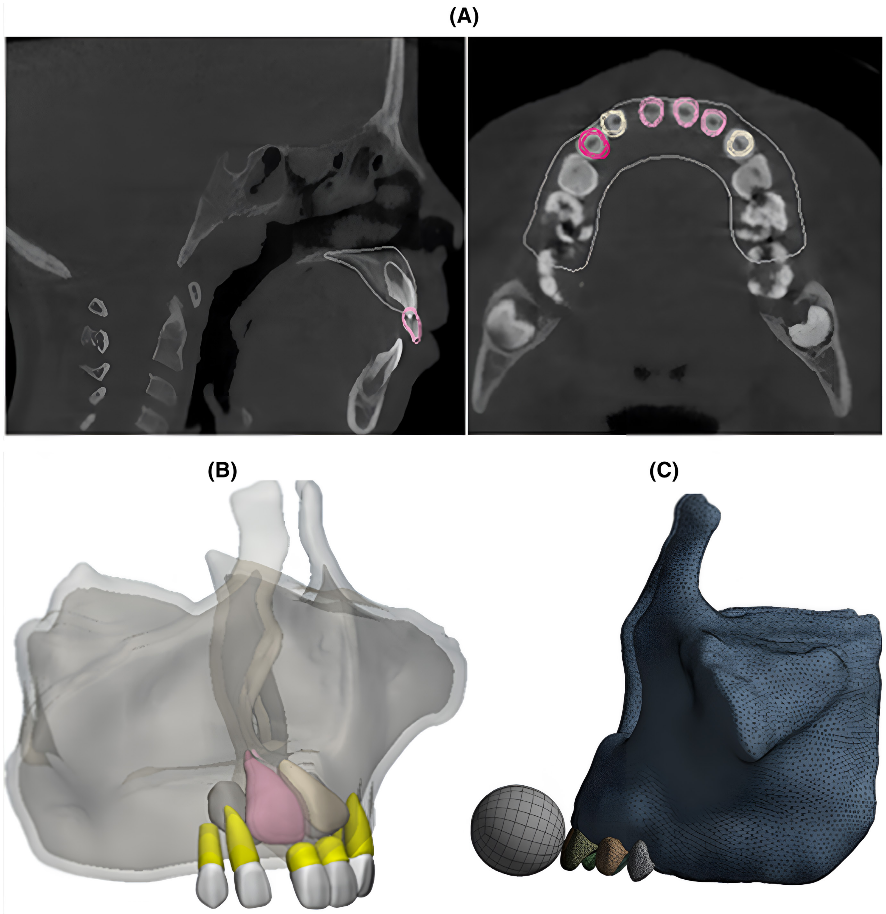

FIGURE 1 Generation of finite element model. (A) A 3D image of the maxillary structure segmented, (B) a 3D model of the maxillary structure, and (C) the mesh structure of the model.

deformation) determined within the scope of this study was carried out in the ANSYS Workbench program.[11] At this stage, the model was integrated into the ANSYS Workbench program, in which analyses will be conducted according to the FEM.

2.3 | Mesh structure

Meshing solid models with the help of the ANSYS Workbench program and determining the finite elements that will best fit the model are crucial steps to obtaining accurate results. For optimum results of the analyses, tetrahedral 8-node finite elements (Solid 92) were used. A mesh size convergence study was performed in the analysis. There is no change in values after a certain value. The mesh size used in the study is the most appropriate mesh size obtained. Elements used in the mesh structure are as follows: determined as 0.075 mm (teeth), 1 mm (maxillary structure), and 4 mm (steel ball) in size and suitable for 3D translation and rotation (x, y, and z axes). The mesh structure of the maxilla was created by combining 593 208 elements with a total of 856 810 node points. The mesh structure of the solid model obtained in the analysis program is modeled as isotropic, homogeneous, and linear elastic (Figure 1C).

2.4 | Material properties

For the FEA, the model's mechanical properties were determined according to the literature and applied to the model to be analyzed.[3,5] In terms of the material properties used, it is assumed that the material properties are isotropic and homogeneous. The dental model is assumed to be linear elastic. For each region, Young's modulus (E), Poisson ratios (ν-isotropic), and the materials' densities were selected per the literature as indicated in Table 1 and defined for the relevant regions.

2.5 | Boundary conditions

As a last analysis step, the boundary and the loading conditions (direction, intensity, and angle of force) were defined. To simulate the impact that caused trauma, a ball with a radius of 10 mm was hit against primary teeth at a speed of 10 m/s. Loading was applied in two different directions: horizontal (buccal) and vertical (incisal) directions. This simulation is given in Figure 2A,B. This situation of trauma simulation was also examined comparatively in both cases by applying a bite load of 100 N to the palatal surface of the incisors.[3] A dynamic FEA was

TABLE 1 Properties of materials used in modeling.

Structure	Elastic modulus (MPa)	Density (g/cm^3)	Poisson's ratio
Enamel	84 100	2.14	0.30 [22]
Dentin	18 600	2.97	0.30 [23]
Periodontal ligament	50	0.95	0.45 [24]
Cancellous bone	1400	0.70	0.31 [25]
Compact bone	13 700	2.00	0.33 [25]
Steel	200 000	0.95	0.30 [26]

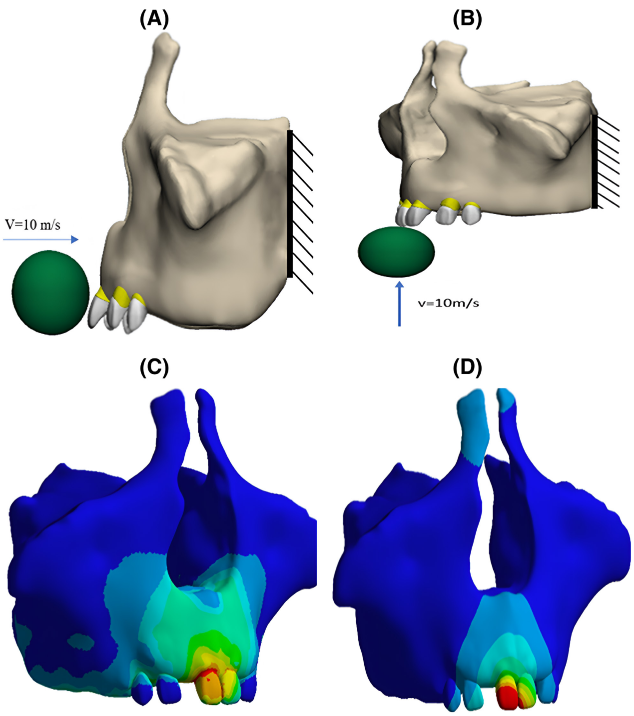

FIGURE 2 Boundary, loading conditions, and model images after analysis. (A) Buccal impact, (B) incisal impact, (C) stress distribution, and (D) deformation distribution.

used in the dental trauma model.[3] The analyses were performed under the determined boundary conditions and loadings using the ANSYS Workbench software, and the obtained results (stress and deformation) were evaluated. Images of the values obtained for each analysis are shown in Figure 2C,D as an example.

3 | RESULTS

In this study, several simulations were conducted to examine the dental trauma model. This analysis aimed to evaluate the stress and deformation distributions in the primary and permanent tooth when it hit a buccal and incisal impact. For this reason, a three-dimensional FEM of the maxillary central incisors, lateral incisors, and canines was composed of a cone scan of a child patient. The stress and deformation distributions were obtained for primary and permanent teeth.

Stress (MPa) and deformation (mm) distributions of the trauma impact are presented in figures utilizing a linear color scale, in which blue shows low values and yellow shows high values (Figures 3–6).

The change in the stress distributions for primary and permanent teeth in the dental model is given in Figures 3 and 4. Figures 3A and 4A show the general stress view of primary and permanent teeth together. The stress distribution in primary and permanent teeth obtained from the analysis is shown in Figures 3B–4B and 3C–4C, respectively. The trauma analyses were performed, and the numerical stress values of primary and permanent teeth results show that the trauma force causes stress in the model. It can be concluded that the stress values are high at the point in which the steel ball contacts for both impact states, and the variation decreases because of distance from the contact surface. Maximum stress values were obtained as 80 and 7.5 MPa for primary and permanent teeth, respectively, for buccal impact (Figure 3). Maximum stress values were obtained as 97 and 25 MPa for primary and permanent teeth, respectively, for incisal impact (Figure 4). Two main results can be seen from the figures. First, the stress values obtained for primary and permanent teeth are quite different. Second, stress values for the incisal impact are greater than for buccal impact (Figure 7).

The deformation distributions obtained from the analysis for the trauma loadings (buccal and incisal impacts) are shown in Figures 5 and 6. Figures 5A and 6A show the general view of primary and permanent teeth together. The deformations in primary and permanent teeth obtained from the analysis are shown in Figures 5B–6B and 5C–6C, respectively. The impacted primary tooth shows the most deformation, but the adjacent teeth and permanent teeth can also move to a certain extent. The deformations for primary teeth obtained from the analysis are shown in Figures 5B and 6B. The results show that impacted primary teeth have the highest deformation values, and the maximum value is 0.2 and 0.35 mm for

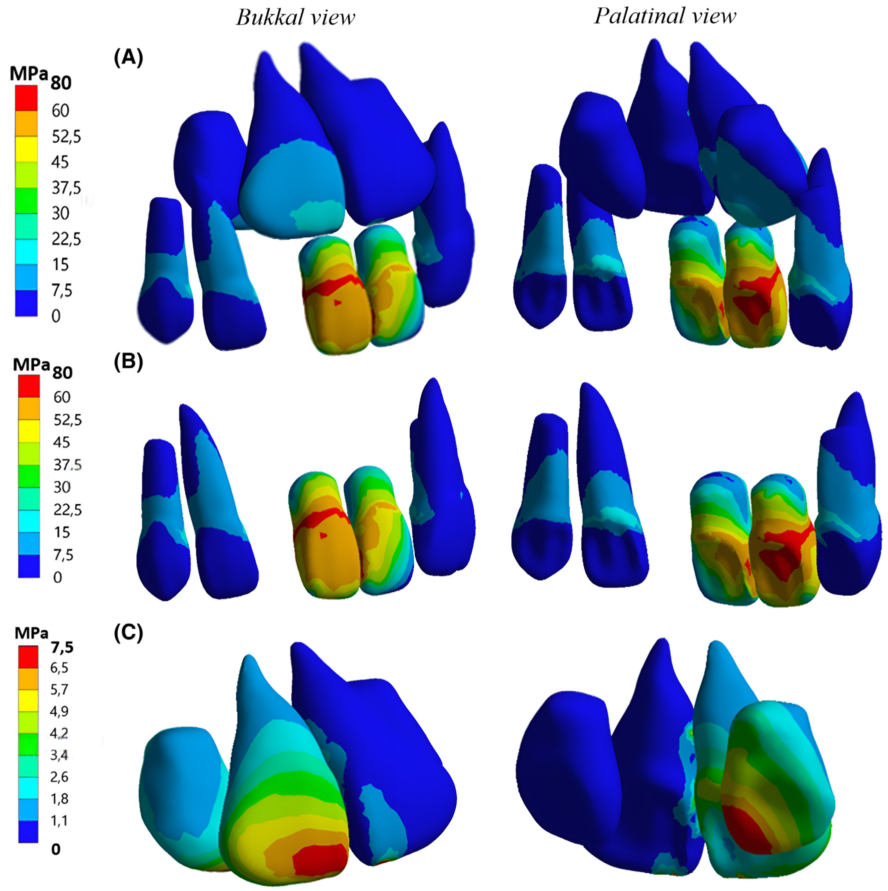

FIGURE 3 Stress distributions for buccal impact. (A) Primary and permanent teeth, (B) primary teeth, and (C) permanent teeth.

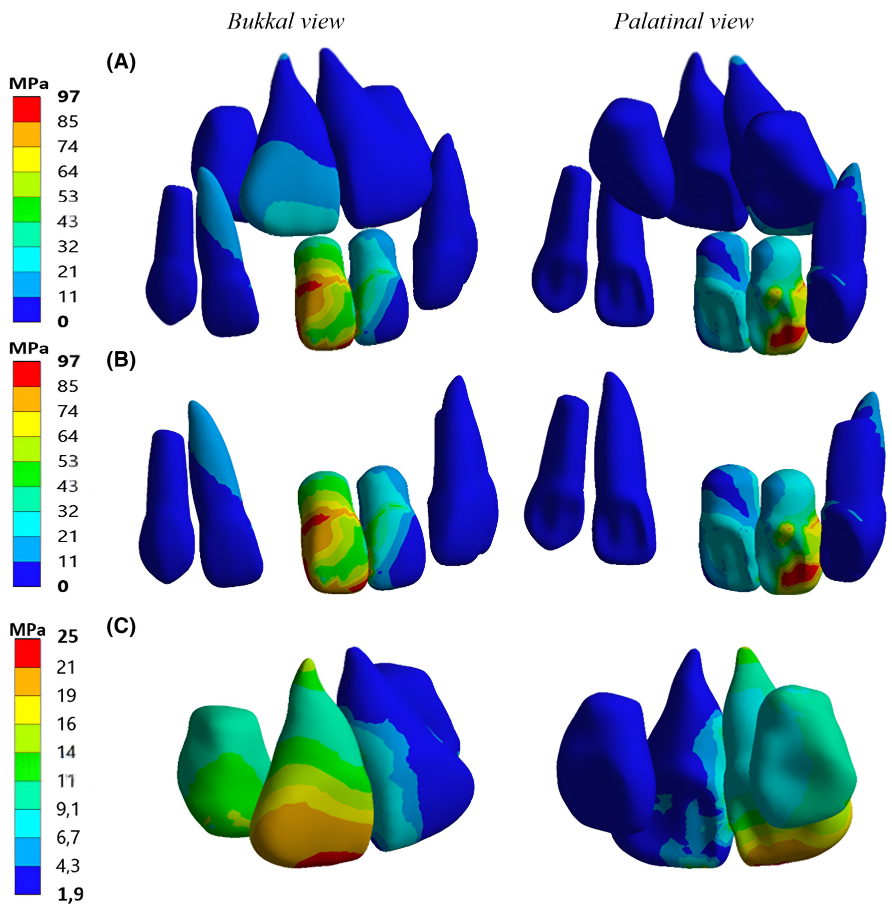

FIGURE 4 Stress distributions for incisal impact. (A) Primary and permanent teeth, (B) primary teeth, and (C) permanent teeth.

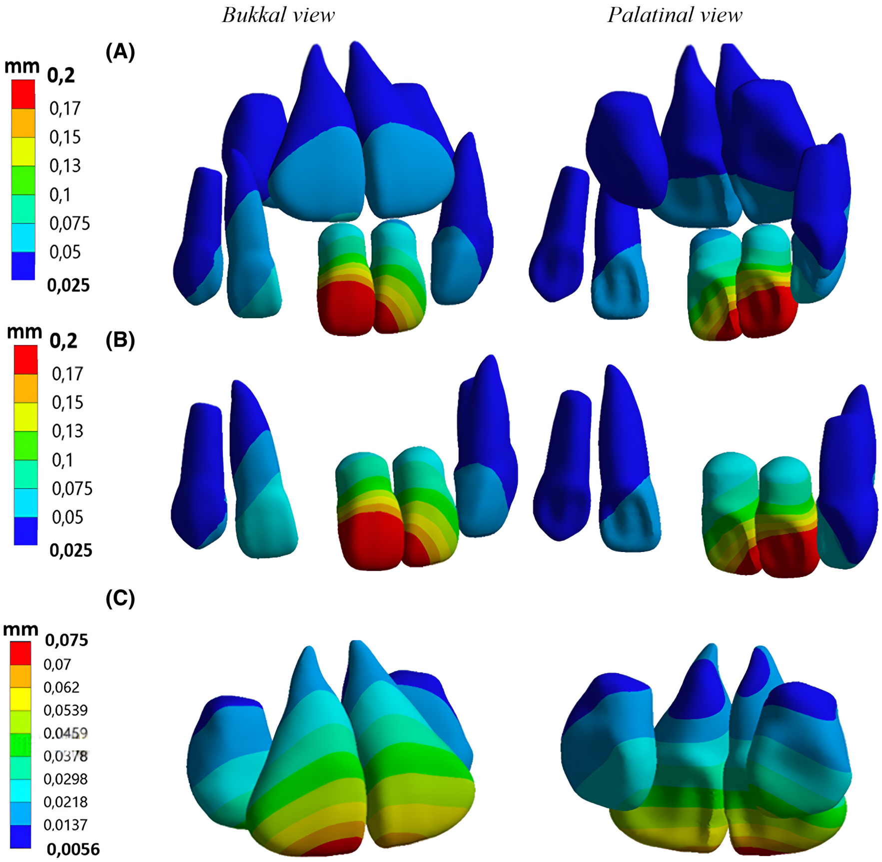

FIGURE 5 Deformation distributions for buccal impact. (A) Primary and permanent teeth, (B) primary teeth, and (C) permanent teeth.

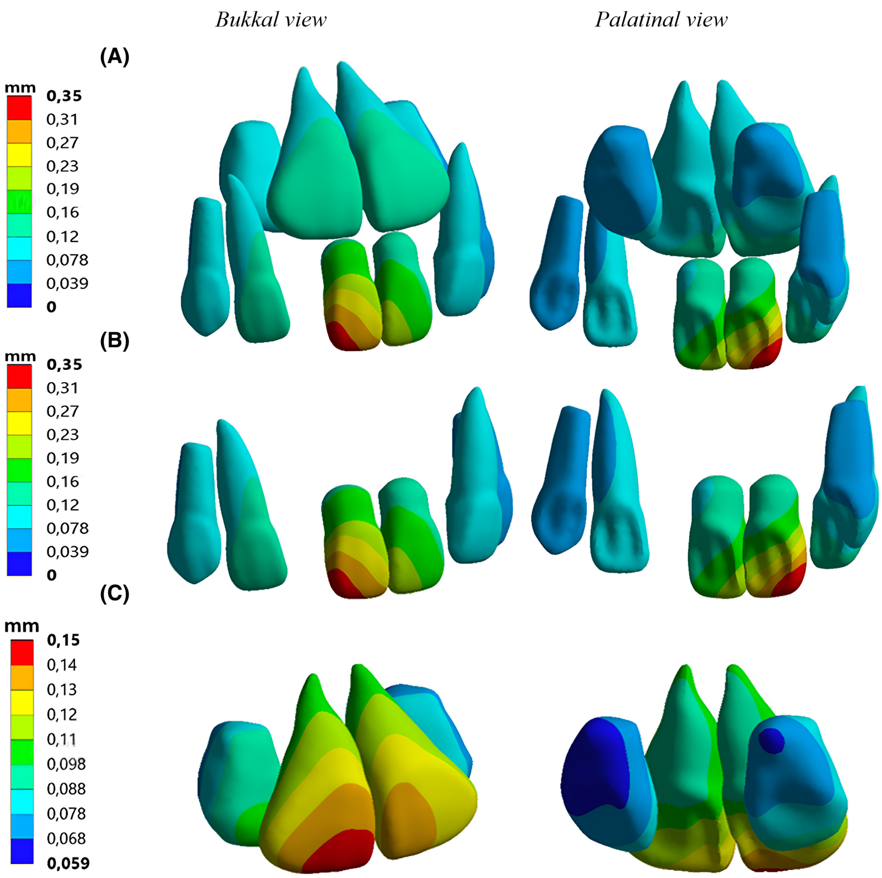

FIGURE 6 Deformation distributions for incisal impact. (A) Primary and permanent teeth, (B) primary teeth, and (C) permanent teeth.

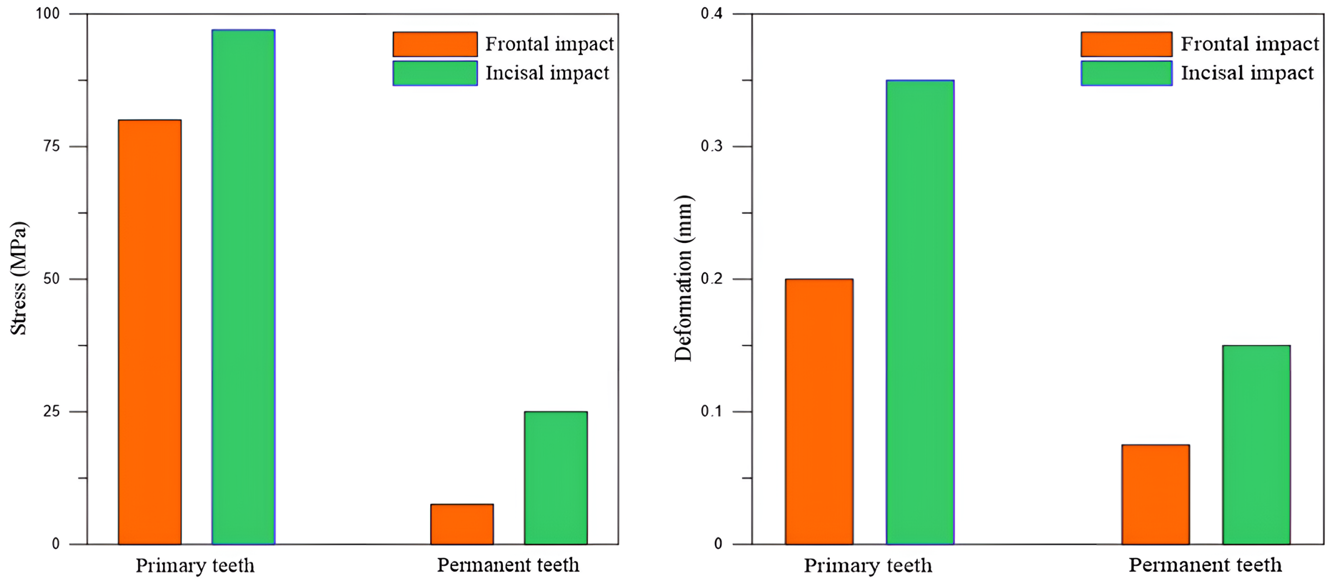

FIGURE 7 Comparison between stress and deformation.

buccal impact and incisal impact, respectively. The deformations for permanent teeth obtained from the analysis are shown in Figures 5C and 6C. When the figure is examined, it is seen that the impact affected permanent teeth. Deformation values, however, did not reach as high as primary teeth, and the maximum value is 0.075 mm for buccal impact and 0.15 mm for incisal impact. The figures clearly show that the two main results for stresses are similar in deformations (Figure 7).

The difference between the stress and deformation values in primary teeth in the forces applied in the buccal and incisal directions is 21% and 75%, respectively; in the permanent tooth germ, this difference was 233% and 100%, respectively.

4 | DISCUSSION

Dental traumas are commonly observed in children, especially during the primary dentition phase. When traumatic forces are applied to primary teeth, damage can occur both in the surrounding tissues of the primary tooth and in the permanent tooth germ.[7] Nonetheless, as this condition is difficult to test, its mechanism still needs to be fully understood.[3] This study used FEM to evaluate the biomechanical effects of the maxillary primary central incisor. Stress and deformation conditions may help explain complications in both permanent and primary teeth. During the analysis, it was observed that the magnitude and direction of the force applied to the primary tooth caused varying patterns of stress and deformation in the permanent tooth germ, the adjacent tooth, and the surrounding tissues. In this study, it has been determined that the forces applied to the maxillary primary central incisor and their directions caused stress and deformation in the surrounding tissues and the permanent tooth germ. Hence, the null hypothesis that the generated force and impact direction would not affect the teeth and the surrounding tissue was rejected.

FEM is a successful method for evaluating biomechanical behaviors and provides a perspective on situations in which experimental testing is not possible. Simulation analyses, like the one performed in this study, are considered ethically appropriate methods since it is not reasonable to replicate dental trauma events for research purposes.[12] In this study, FEA was performed with a primary upper central incisor model exposed to simulated buccal and incisal trauma. CBCT data were used to model primary teeth, the adjacent teeth, the surrounding tissues, and the permanent tooth germs. Simulation models created using CBCT images, which provide robust data about the patient, enable the closest possible replication of reality.[8] Numerous studies in the literature utilize the FEM and CBCT to create models.[3,5,13]

Another factor to consider is the most accurate expression of the mechanical properties of each material that makes up FEM.[14] Each material has its own unique mechanical properties.[15] Although dentin, pulp, periodontal ligament, and cortical and cancellous bone regions behave isotropic in the dentoalveolar articulation structure, tooth enamel behaves like an anisotropic material due to the arrangement of its prisms.[16] In FEM studies, material properties such as Poisson's ratio, Young's modulus, and the density of each material should be considered as part of the material-related factors.[17,18] These factors related to the material provide insights into how the material will respond to applied forces in the simulation environment.[15,16] Since material properties for oral structures cannot be determined in situ, the references we used in this study are based on references from the published laboratory studies.[3,5]

After creating the FEM model, the magnitude and duration of the force must be determined in the study.[19] Studies in the literature evaluate different magnitudes of forces at various time intervals.[3,5,19] According to Miura and Maeda,[20] applying a 100-N force for 1.5 ms can cause avulsion of the maxillary central tooth. In the literature, some studies simulate low- to moderate-level dental traumas by applying a force of 800 N for 4 ms.[15–18] The biting force in humans is commonly estimated to be around 100 N. Therefore, this force value is frequently used in FEM studies to simulate chewing forces.[3] Silva et al.[21] applied a high force of 2000 N for 4 ms to simulate traumatic injuries in both the buccal and incisal directions. They explained that such a large force was used due to the lack of trauma studies using strong forces. The impact velocity of 10 m/s used in this study simulates scenarios such as a patient involved in a bicycle crash, accident, or fall. This builds on previous studies that have shown that bicycle accidents are common causes of dental trauma.[22,23]

Dental trauma model in our study utilized dynamic FEM. The dynamic analysis focused on the maxillary central incisor in most of the FE models of tooth trauma.[17,18,20,21] Such analysis was chosen for the dental trauma model to achieve a more realistic simulation, considering its ability to incorporate dynamic factors.[15,16,18,20] Additionally, dynamic analyses seem more appropriate for models with short-term traumatic loading, as in our study.[24] Furthermore, in addition to all these, dental trauma studies utilizing static analysis have been conducted, considering the lower computational cost of static analysis compared with dynamic analyses.[13,24] In one of these studies, it was stated that the inertia of tooth structures did not affect trauma simulation, and the results were similar to dynamic analysis.[13] It has been stated that static analysis is an acceptable method for dental trauma model studies.[13,24] In addition, there are studies emphasizing the difference between dynamic and static analysis, stating that at high loading rates, the inertia forces of dental structures cannot be neglected.[3,5,8] With all this information, in light of the short-term, high-velocity trauma model created, dynamic analysis has been preferred for the most realistic simulation without neglecting the inertia of dental structures.

A previous study has indicated that even low forces, such as 1 m/s = 3.6 km/s, can cause harm to the permanent tooth germ.[25] Traumatic events experienced at a younger age cause more severe damage to permanent tooth development.[5,25] In this study, we observed that the force applied to a primary tooth with more than half of its root resorbed creates stress and deformation in the permanent tooth germ. Vilela et al.[5] in their study using FEM, looked at the effect of forces on primary teeth with three different root resorptions on the permanent tooth germ. It has been observed that the impact on the primary incisor with no resorption (3.5-year-old children) causes less stress and deformation in the permanent tooth germ than the teeth with more root resorption (5–6 years). This result has been attributed to the cortical bone between the primary incisor tooth and the permanent tooth germ. They explained this situation with the presence of a cortical bone barrier between the primary incisor and the permanent tooth germ. The absence of bone tissue in 6-year-old children, however, has increased the stress and deformation in the permanent tooth germ in response to dental forces. Similarly, this study's primary tooth with high root resorption created high stress and deformation areas on the permanent tooth germ.

Stress and deformations are transferred to the teeth and bone by the PDL.[26] Therefore, bone tissue can be damaged when the PDL is injured, and tooth mobility can occur. This condition can lead to impaired vascular blood flow and pulp necrosis.[27] Vilela et al.[3] showed that the force on the central incisor causes displacement in the root of the adjacent teeth. Significant stress concentrations were observed on the palatal, proximal, and labial surfaces of the teeth adjacent to the traumatized incisor. Stresses occurring in the adjacent teeth were higher than the force values generated during biting. Deformations were observed in the root regions of the adjacent teeth in which the force was applied to the tooth. Dezzen-Gomide et al.,[13] in their study, applied buccal and incisal forces to the maxillary central teeth at different root development stages. Trauma from forces applied in the buccal direction resulted in higher stress values, regardless of the stage of root development. Teeth with fully formed roots exhibited higher stress values in the crown region. Incisal trauma caused more stress on the dental papilla in proportion to the root development stage. Oskui et al.[24] noted that the mechanical properties of the PDL are important in the duration of force application and semi-static loading in dental traumatic forces. Silva et al.[21] analyzed the stress distribution in the dentoalveolar structures of the upper central incisor exposed to both buccal and incisal forces. In this study, using a 3D FEM, a force of 2000 N acting on the buccal surface of the crown at an angle of 90° and a vertical force of 2000 N acting on the incisal surface of the tooth in the cleidocranial direction were applied. Similar to the results of this study, harmful stresses that damage both the tooth and the adjacent tissue were observed in both cases. They, however, revealed that the damage in soft tissues, such as the periodontal ligament and dental pulp, is negligible, and trauma causes more damage to the hard tissue structures attached to the tooth. In this study, stress and strain areas were also observed on the buccal, palatal, and approximal surfaces of the primary lateral and canine teeth adjacent to the maxillary primary incisor, in which both buccal and incisal forces were applied. It has been observed that incisal forces have a greater effect and lead to higher deformation than buccal forces. This supports the importance of the previously proposed impact direction on the severity of eventual damage.[3,28] Buccal forces can result in palatal or labial displacement of the permanent tooth germ.[29] Incisal forces can compress the permanent tooth germ within the bony structure, leading to traumatic injuries such as intrusion and/or lateral luxation.[30]

Evaluating the dynamic effects of dental trauma and the resulting consequences on the adjacent teeth and the permanent tooth germs is a complex process.[3] In this study, FEM was used to simulate the effect of dental trauma on a model created from CBCT images of a child. This analysis has limitations, such as the inability to replicate material properties and tissues precisely as they exist in the natural environment. In this study, forces in different directions applied to primary teeth help to clarify the question marks about clinically observed complications in both the impacted permanent tooth germ and the adjacent teeth.

To the authors' knowledge, no study has yet demonstrated the combined effect of two directional forces applied to the maxillary primary incisor on both the permanent tooth germ and the adjacent teeth. The results of this study have demonstrated that the forces applied to primary teeth can induce stress and deformation not only in the adjacent teeth but also in the permanent tooth germs. Based on these findings, it is important to consider the traumatized primary tooth and the clinical and radiographic examination of the dentoalveolar tissues of the adjacent teeth in patients presenting with dental trauma. The traumatic impact should also be evaluated regarding the permanent tooth germs, emphasizing the importance of long-term trauma monitoring for root resorption and ankylosis formation. This approach allows for early diagnosis and treatment, contributing to the long-term retention of teeth in the oral cavity.

The study's findings revealed that the stresses and deformations in primary teeth were higher than those in the permanent tooth germs. The effect on the incisal edge created higher stress values in both primary teeth and the permanent tooth germ than in the buccal direction. The impact on the incisal edge caused higher stresses and deformations than buccal impact. Post-traumatic stress in primary teeth was higher than in the permanent tooth germ. Again, the incisal edge created higher deformation values than the buccal edge.

AUTHOR CONTRIBUTIONS

A.K. and M.Y. conceived the ideas; A.K., M.Y., M.E.N., and B.Ç. collected the data; M.Y., A.D., E.U.Y., and Ş.Ö. analyzed the data; and A.K., M.Y., and M.E.N. led the writing.

FUNDING INFORMATION

There is no funding.

CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS APPROVAL STATEMENT

The required ethics committee decision for the study was obtained from the Non-Invasive Ethics Committee, Recep Tayyip Erdogan University Faculty of Medicine (approval number: 2023/133).

PATIENT CONSENT STATEMENT

Consent and institutional permission were obtained from the patient whose image was used.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

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CLINICAL TRIAL REGISTRATION

The study is not a clinical trial.

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How to cite this article: Kurt A, Yaylacı M, Dizdar A, et al. Evaluation of the effect on the permanent tooth germ and the adjacent teeth by finite element impact analysis in the traumatized primary tooth. *Int J Paediatr Dent*. 2024;00:1-10. doi:10.1111/ipd.13183