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Evaluation of the effect of reverse curved spee Ni-Ti wires with different depths in MBT and Roth brackets on mandibular teeth during leveling and alignment using finite element analysis

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Abstract

Objective The aim of our study is to analyze the forces generated by reverse curve archwires with three different depths and two different dimensions for Roth-type brackets and MBT-type brackets through finite element analysis (FEA) to assess their effects.

Materials and methods This study involves modeling wires of different dimensions and depths (20 mm, 25 mm and 30 mm) for Roth-type brackets with 0.018″slot size and MBT-type brackets with 0.022″slot size. 12 linear static analyses were conducted under specific loading and boundary conditions to evaluate tooth movements along the X, Y, and Z axes, total displacement, and von Mises stresses on the periodontal ligament (PDL).

Results 0.022 slot MBT bracket with reverse curve of spee wire 0.019 × 0.025″and 0.021 × 0.025″ dimensions and 30 mm depth, 0.018 slot Roth bracket with 0.017 × 0.025″ and 0.016 × 0.022″ wire and 30 mm depth applied the most aggressive forces, leading to high displacement and PDL stress. In contrast, 0.022 slot MBT bracket with reverse curve of spee wire 0.019 × 0.025″ dimensions and 20 mm depth, 0.018 slot Roth bracket with reverse curve of spee wire 0.017 × 0.025″, 0.016 × 0.022″and 25 mm depth, 0.017 × 0.025″, 0.016 × 0.022″and 20 mm depth demonstrated more conservative force applications.

Conclusion This comparative analysis of 12 different models demonstrates that varying orthodontic forces have a significant impact on both tooth movement and PDL stress. These findings highlight the significance of selecting the appropriate model based on the patient's periodontal health to ensure orthodontic treatments are performed effectively and safe.

Keywords Reverse curved spee wires, Finite element analysis, Mbt, Roth, Orthodontics, Root resorpsion

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Introduction

The Curve of Spee (COS), first described by F. Graf von Spee in 1890, refers to the natural occlusal curvature of human dentition. This curve, which connects the mandibular condyle, the second molars, and the incisal edges of the lower incisors, plays important role for efficient mastication [1]. Orthodontic treatment often aims to flatten this curve to achieve occlusal stability and correct deep bites. This is commonly done using reverse curve archwires, which extrude lower premolars and minimally intrude lower incisors, according to Tweed's orthodontic philosophy [2]. Two major bracket systems, Roth and MBT, include the correction of the Curve of Spee in their treatment protocols. Roth's system overcorrects deep bites and flattens the curve through precise torque adjustments [3], while the MBT system utilizes lighter forces and archwires designed to level the occlusal plane [4]. Correcting the Curve of Spee can be achieved through molar extrusion, incisor intrusion, or both, depending on the patient's facial esthetics, occlusal plane stability, and functional needs [5]. Reverse curve archwires are key to correcting deep bites, and Ni-Ti archwires with exaggerated Spee curvature are particularly especially effective for initial bracket engagement in orthodontic systems [6].

Applying orthodontic force to a tooth with reduced periodontal support may lead to circulatory issues, potentially impacting the treatment's clinical effectiveness and outcomes [7–10]. Vascular disruptions and periodontal degradation are influenced by factors such as the type, application point, force magnitude, and duration of orthodontic force [7–9, 11, 12]. FEA is a widely utilized mathematical approach for analyzing stress within the periodontium. It enables the evaluation of stress patterns by examining how forces are absorbed and dissipated across human anatomical structures [11, 12]. FEA allows detailed assessment of stress distribution and tooth movement, providing insights that help orthodontists optimize treatment forces and predict outcomes, minimizing risks such as root resorptions [13].

The aim of our study is to evaluate the forces applied by reverse curve Spee archwires of different depths in 0.018" slot Roth and 0.022" slot MBT bracket types using FEA. By considering individual factors such as patients' periodontal health and lower incisor inclinations, this research aims to support the development of customized treatment plans aligned with each patient's specific needs.

Materials and method

Finite element analysis, including stress analysis, was performed using HP workstations with 2.40 GHz INTEL Xeon E-2286 processors and 64 GB ECC memory. The bone model was obtained from the Visible Human Project, and bone and tooth models were processed in 3DSlicer software and exported in.stl format. Reverse engineering and 3D CAD operations were completed using ANSYS Spaceclaim (Concord, Massachusetts, USA), while meshing and analysis were carried out in ANSYS Workbench. LS-DYNA was used for solving the finite element models. The mandibular bone model was created from Visible Human Project tomography data with 0.33 mm slice thickness. Data was segmented in 3DSlicer software, cleaned of unwanted areas, and converted into 3D models. Cortical bone, trabecular bone, teeth, and periodontal ligament were modeled in ANSYS Spaceclaim. Teeth were based on Wheeler's atlas, and ligament thickness was set at 0.2 mm. The depth of the Spee curve in the model (Fig. 1) was determined to be 2.4 mm.

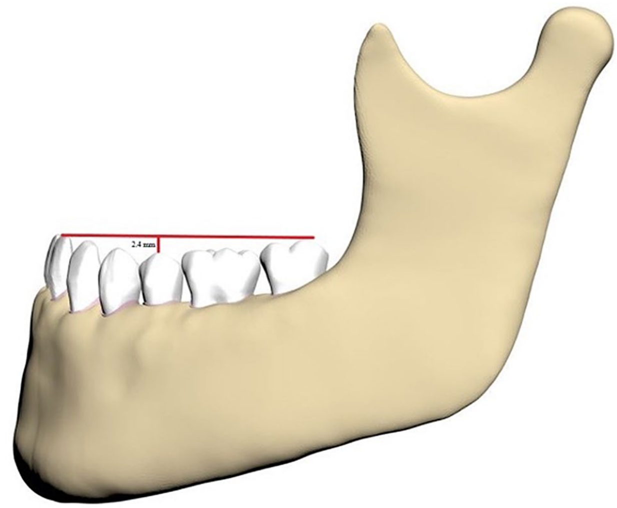

Fig. 1 The depth of the curve of Spee in the modeled mandible

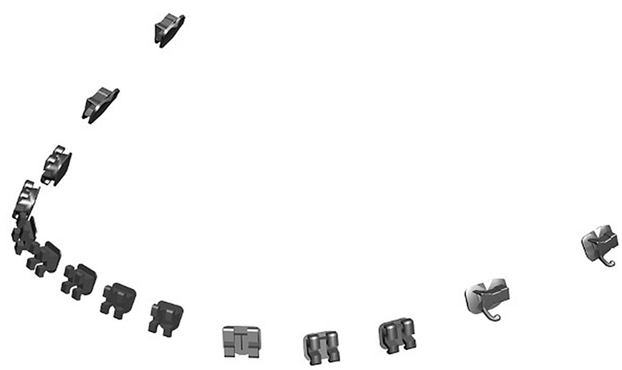

Fig. 2 The image of brackets modeled in the MBT system in FEA

Fairfield (Stratford, CT, USA) American Orthodontics (Sheboygan, Wisconsin, USA) and RMO (Franklin, Indiana, USA) brand wires for MBT (Fig. 2) and Roth (Fig. 3) system brackets were modeled in ANSYS Spaceclaim. Brackets were modeled according to the American Orthodontics Master Series brackets. The torque, angulation and rotation values used in MBT (Table 1) and Roth brackets are shown in Table 2.

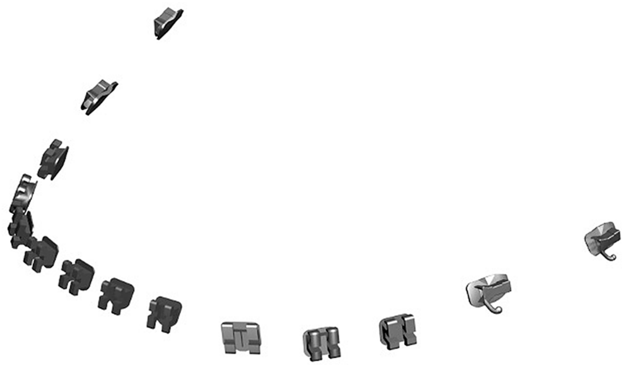

Fig. 3 The image of brackets modeled in the Roth system in FEA

Table 1 The torque, angulation and rotation values used in MBT brackets

0.022"MBT System	Torque	Angulation	Rotation
Anteriors	-6 °	0°	0°
Cuspid	-6°	+3°	2°
1st Bicuspid	-12°	+2°	0°
2nd Bicuspid	-17°	+2°	0°
1st Molar Tube	-20°		0°
2nd Molar Tube	-25°		0°

Table 2 The torque, angulation and rotation values used in Roth brackets

0.018"Roth System	Torque	Angulation	Rotation
Anteriors	0 °	0°	0°
Cuspid	-11°	+7°	2°
1st Bicuspid	-17°	0°	4°
2nd Bicuspid	-22°	0°	4°
1st Molar Tube	-10°		0°
2nd Molar Tube	-30°		7°

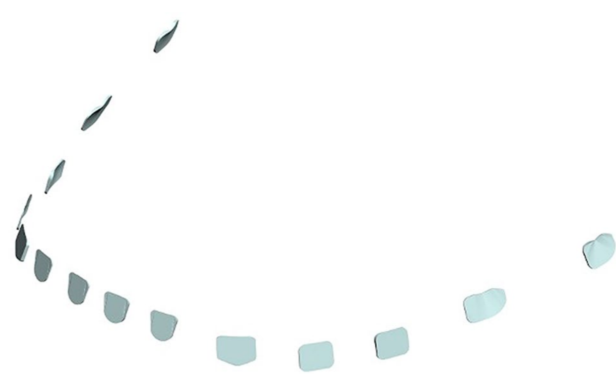

Fig. 4 The image of modeled composite layers in FEA analysis

Composite layers were limited to 0.1 mm in thickness (Fig. 4). In our FE model, 'surface-to-surface contact' was defined between the gingival and occlusal slot walls of the bracket and the archwire, using program-controlled formulation. Similar contacts were also defined between the base of the bracket and the base of the archwire. The frictional resistance of the archwire edges within the slot was also considered in the model. The coefficient of friction (μ) between the contact surfaces was assigned a value of 0.13 [14, 15].

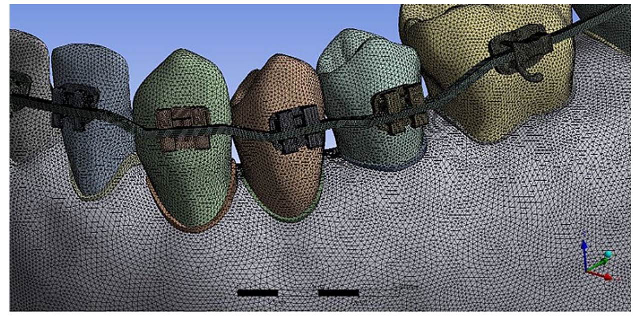

Fig. 5 The mesh structure of the model used in the FEA

Force transmission was achieved by aligning mesh structures (Fig. 5) in ANSYS Workbench. Mathematical models were generated by meshing geometric models with tria (0.1–0.25 mm) and tetrahedral solid meshes in ANSYS Workbench.

During the development of the mathematical models (mesh structures) in the study, highly precise tria (triangular) mesh sizes ranging from 0.1 to 0.25 mm were used. After meshing all model surfaces with triangular meshes known as tria, the solid meshes of the objects were generated using tetrahedral (regular tetrahedron) solid mesh types. These models were then transferred to the LS-DYNA solver for analysis.

In all models, forces were applied to the wires attached to the lower incisor teeth (Fig. 6). The forces applied by the wires to the incisors were measured using a Dentaurum measuring gauge (measuring range 25–250 g).

The magnitudes of the forces applied in the analysis models are given below (Table 3).

Study models

In the analyses, linear material properties with the given elastic modulus and Poisson's ratio were used (Table 4). The material properties of the analyzed model were numerically defined. All materials are homogeneous, linear, and isotropic, consistent with the majority of published studies [15–19].

The models were fixed by constraining all degrees of freedom at the superior and posterior regions of the bone, preventing movement in all three axes. A boundary condition was applied to all parts of the model such that it was symmetric with respect to the Y-Z plane and normal to the X-axis.A total of 12 linear static analyses (Table 5) were performed under the specified forces and boundary conditions (Fig. 8).

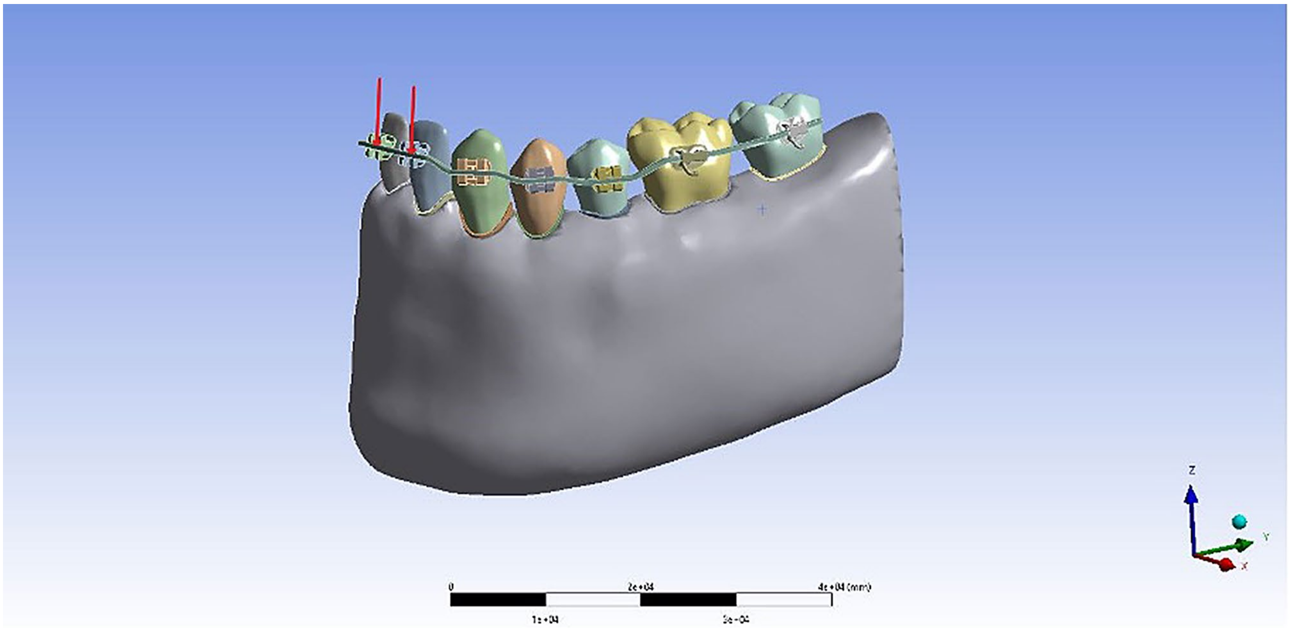

Fig. 6 The direction of the applied force in the FEA model

Table 3 The specifications of the brackets and wires used in the study

Model 01	**0.022 slot MBT bracket with 0.019 × 0.025″ dimensions 30 mm depth wire applies 60 g forces (Fig. 7)**
Model 02	0.022 slot MBT bracket with 0.021 × 0.025 ″dimensions 30 mm depth wire applies 65 g forces
Model 03	0.022 slot MBT bracket with 0.019 × 0.025″ dimensions 25 mm depth wire applies 36 g forces
Model 04	0.022 slot MBT bracket with 0.021 × 0.025 ″dimensions 25 mm depth wire applies 40 g forces
Model 05	0.022 slot MBT bracket with 0.019 × 0.025″ dimensions 20 mm depth wire applies 24 g forces
Model 06	0.022 slot MBT bracket with 0.021 × 0.025″ dimensions 20 mm depth wire applies 25 g forces
Model 07	0.018 slot Roth bracket with 0.017 × 0.025″ dimensions 30 mm depth wire applies 54 g forces
Model 08	0.018 slot Roth bracket with 0.016 × 0.022″ dimensions 30 mm depth wire applies 52 g forces
Model 09	0.018 slot Roth bracket with 0.017 × 0.025″ dimensions 25 mm depth wire applies 34 g forces
Model 10	0.018 slot Roth bracket with 0.016 × 0.022″ dimensions 25 mm depth wire applies 30 g forces
Model 11	0.018 slot Roth bracket with 0.017 × 0.025″ dimensions 20 mm depth wire applies 23 g forces
Model 12	0.018 slot Roth bracket with 0.016 × 0.022″ dimensions 20 mm depth wire applies 20 g forces

Results

This study examines the effects of varying orthodontic forces across 12 models, with a focus on tooth displacement and periodontal ligament stress. These models range from highly aggressive force applications (Models 1, 2, 7, and 8) to more conservative approaches (Models 5, 11, and 12). The analysis highlights the variation in force magnitude and its impact on tooth movement and PDL.

The total displacement of the incisal edge and root apex of the lower incisors in all models is shown in the form of a bar chart (Fig. 9).

Models 1(Fig. 10) and Model 2 (Fig. 11) showed the highest displacement magnitudes, particularly for the central incisors with values reaching 2.620E-04 mm and 2.821E-04 mm. These models apply strong forces aimed at significant tooth movement.

Models 7 and 8 also demonstrated high displacement magnitudes, with 2.361E-04 mm and 2.311E-04 mm for the central incisors.

Model 5 (Fig. 12), Model 10(Fig. 13), Model 11(Fig. 14), and Model 12 (Fig. 15) showed lower displacement values. For instance, Model 5 showed a displacement of 1.044E-04 mm, while Model 11 displayed the smallest displacement at 1.004E-04 mm.

Model 5 and Model 6 show the lowest displacement and PDL stress values, indicating a more controlled and balanced force application.

Directional displacements (X, Y, Z)

X-direction: All models exhibited relatively low X-direction (lateral) displacement. However, Models 1 and 2 showed slightly more lateral movement compared to other models, particularly in the lateral incisors and canines. On the other hand, Models 5, 11, and 12 had

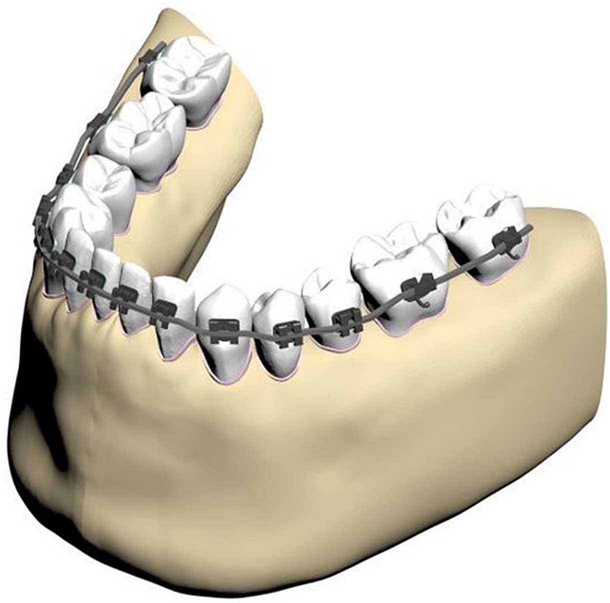

Fig. 7 The image of 0.022 slot MBT bracket with 0.019 × 0.025″ dimensions 30 mm depth wire (Model 1) in FEA

Table 4 Mechanical properties of materials used for FEA in this study [16]

Material	Elastic Modulus [MPa]	Poisson's Ratio [v]
Cortical Bone	13,700	0.3
Cancellous Bone	1370	0.33
Tooth	20,000	0.3
PDL	50	0.49
Nickel-Titanium	44,000	0.33
Stainless Steel	200,000	0.3
Composite	8823	0.25

Table 5 Information for the twelve analysis models created

	Total # of Nodes	Total # of Elements
Model 1	407,132	1,538,090
Model 2	408,791	1,539,623
Model 3	407,132	1,538,090
Model 4	408,791	1,539,623
Model 5	407,132	1,538,090
Model 6	408,791	1,539,623
Model 7	404,103	1,533,592
Model 8	403,527	1,528,200
Model 9	404,103	1,533,592
Model 10	403,527	1,528,200
Model 11	404,103	1,533,592
Model 12	403,527	1,528,200

minimal lateral displacement, reflecting stability in these teeth.

Y-direction (intrusion): The intrusion movement occurred primarily in Models 1, 2, 7 and 8. Model 2 having the highest intrusion of -2.683E-04 mm for the central incisors. Models 11 and 12 displayed the least intrusion, with – 9.555E-05 mm and – 8.453E-05 mm.

Z-direction (anteroposterior movement): Models 7 and 8 showed the highest Z-direction displacement, with the central incisors moving – 6.946E-05 mm and – 6.735E-05 mm. Models 09, 10, and 11 displayed more conservative anteroposterior movement.

Comparison of Displacement Effects in Models with 0.022 Slot MBT Brackets:

The FEA images display the displacement magnitudes of the lower incisors in Models 1 to 6, with a color gradient representing the intensity of movement (Fig. 16). The red areas indicate the highest displacement, while the blue regions show the least movement. Model 1 and Model 2 exhibit the greatest displacement, particularly in the incisal region, suggesting that these models generate higher force levels on the lower incisors. Model 3 and Model 4 demonstrate moderate displacement, indicating a more balanced force application. Model 5 and Model 6 show the least displacement, suggesting that these models apply more controlled forces, reducing stress on the periodontal ligament.

Comparison of displacement effects in models with 0.018 slot Roth brackets

The FEA images illustrate the displacement magnitudes of the lower incisors in Models 7 to 12, with a color gradient indicating the level of movement (Fig. 17). Model 7 and Model 8 exhibit the highest incisal displacement, suggesting that these models apply higher forces, leading to significant incisor movement. Model 9 and Model 10 display moderate displacement, indicating a more controlled force application compared to the first two models. Model 11 and Model 12 show the least movement, suggesting that these models provide the most stable and conservative force application, reducing excessive tooth movement and potential periodontal stress. These findings emphasize the effect of wire dimensions and force magnitudes in Roth bracket models, highlighting the importance of choosing appropriate mechanics to ensure effective yet safe tooth movement, minimizing root resorption risks and excessive proclination.

Von Mises stresses

Models 1 and 2 showed the highest PDL stress values, with central incisor stress reaching 9.049E-03 MPa and 9.758E-03 MPa. Models 7 and 8 demonstrated similarly high PDL stress levels, with 8.135E-03 MPa and 7.918E-03 MPa on the central incisors. Models 9, 10, 11, and 12 showed lower stress values, making them more suitable for gradual tooth movement. Model 12, for example, exhibited 3.043E-03 MPa on the central incisor, emphasizing its conservative approach, which minimizes the risk of PDL overloading. Model 11, the most conservative

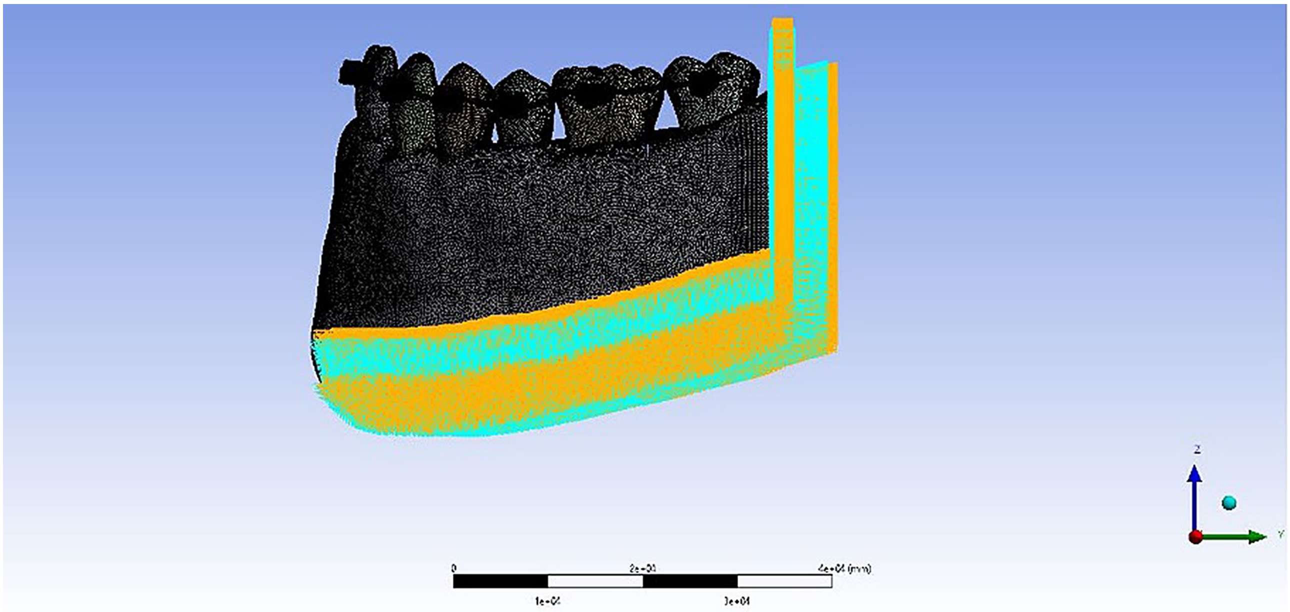

Fig. 8 The image of boundary conditions in FEA model

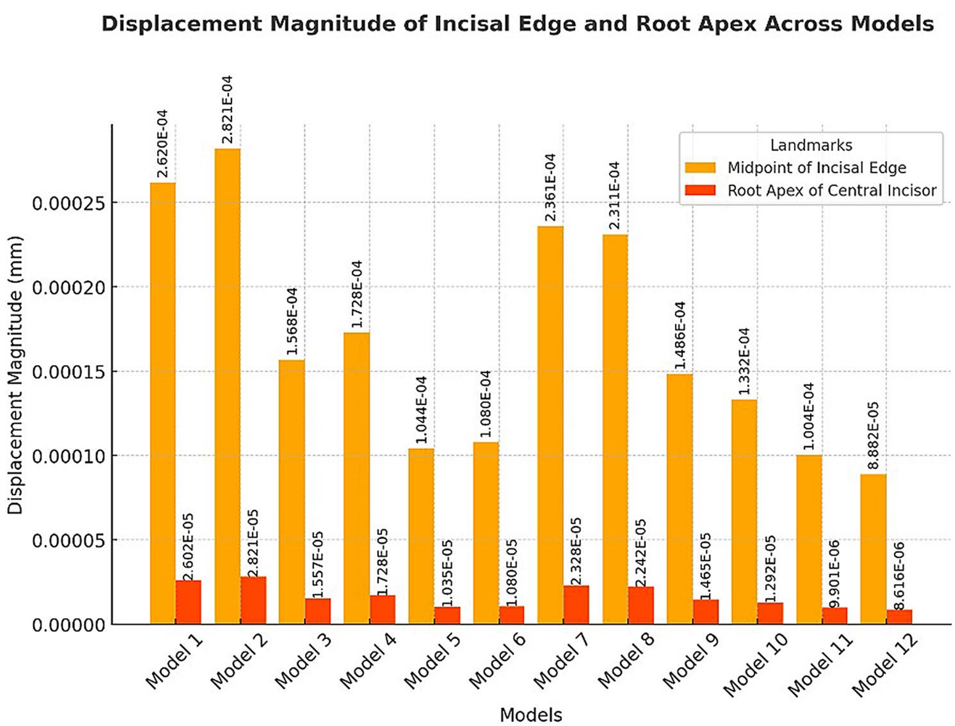

Fig. 9 Comparison of the total displacement amount at the incisal edge and root apex of the lower incisors in all models

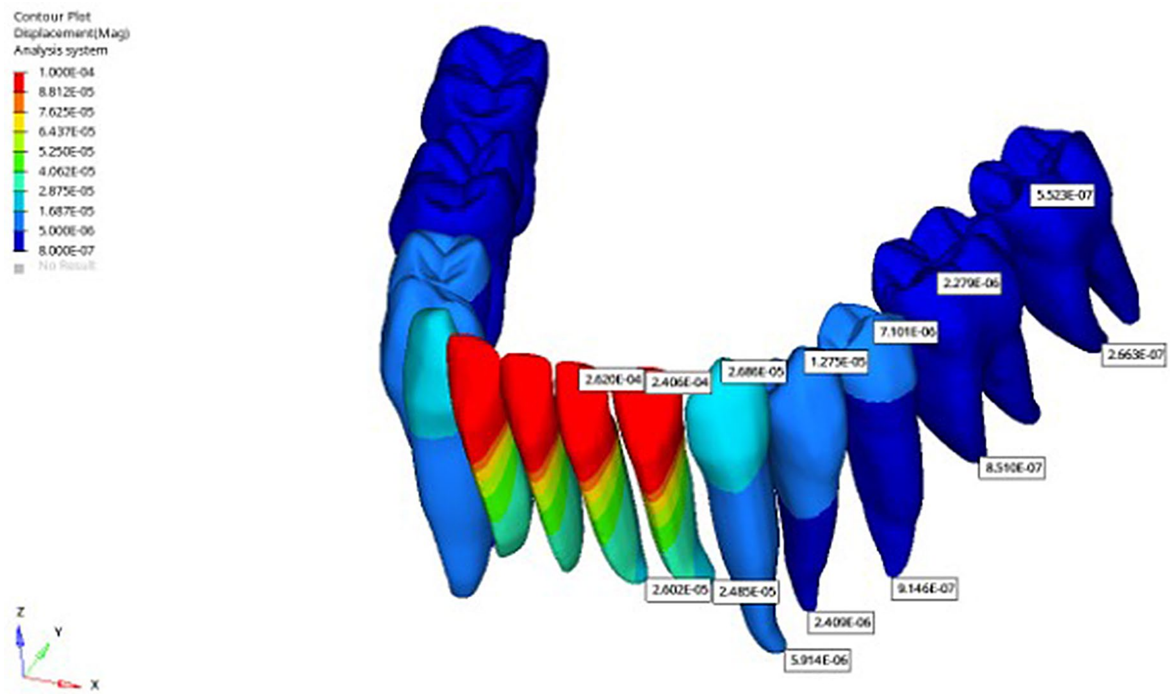

Fig. 10 FEA image of the total displacement of the Model 1

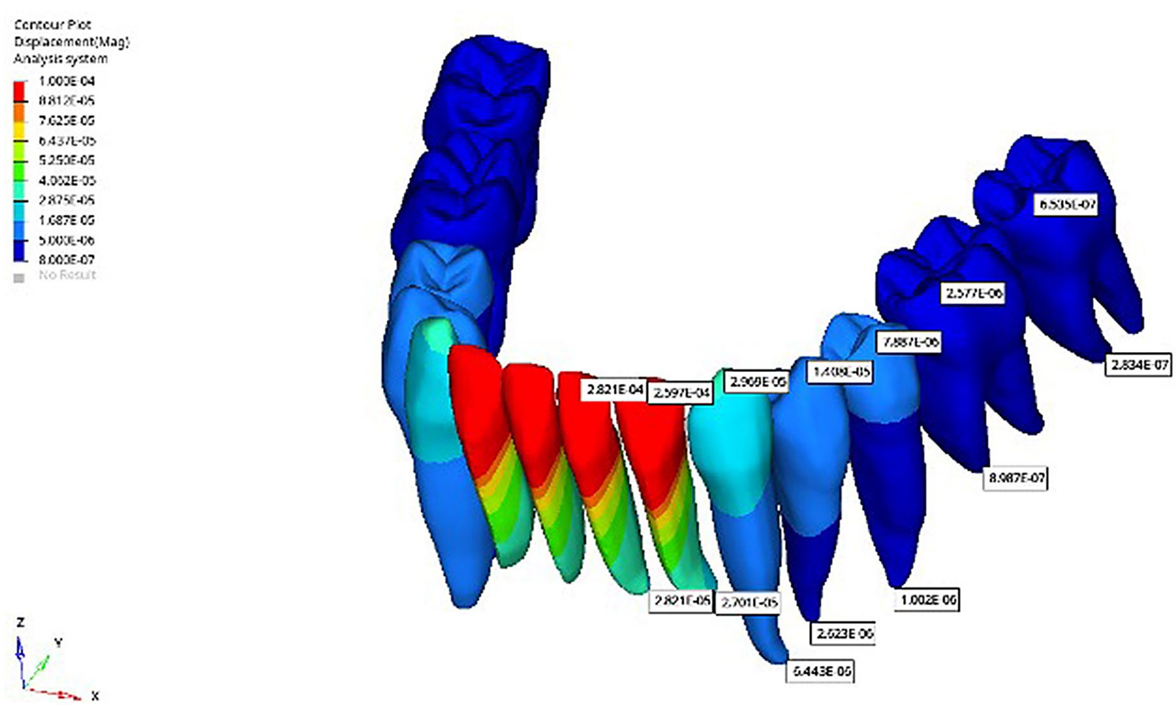

Fig. 11 FEA image of the total displacement of the Model 2

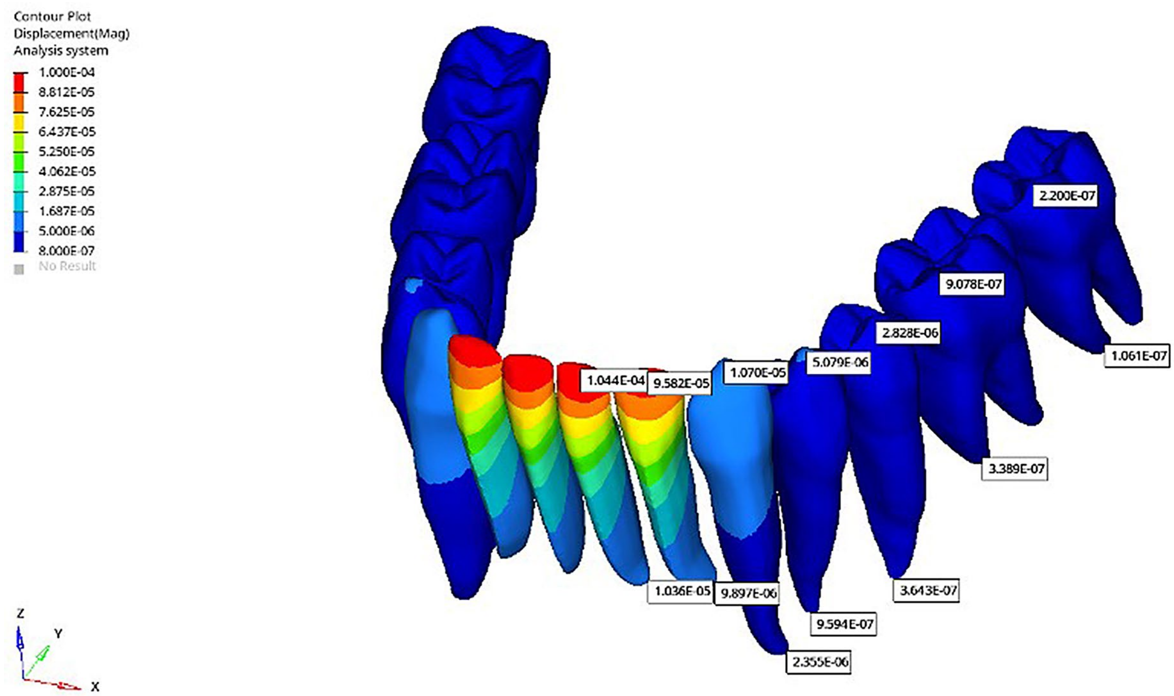

Fig. 12 FEA image of the total displacement of the Model 5

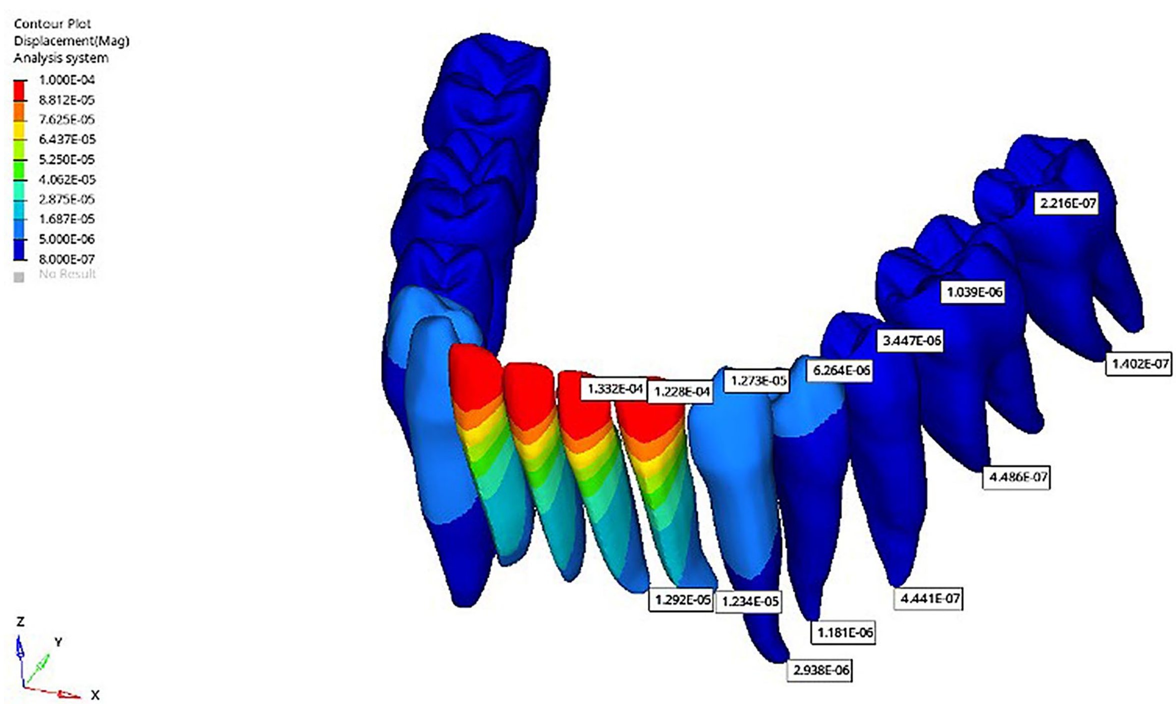

Fig. 13 FEA image of the total displacement of the Model 10

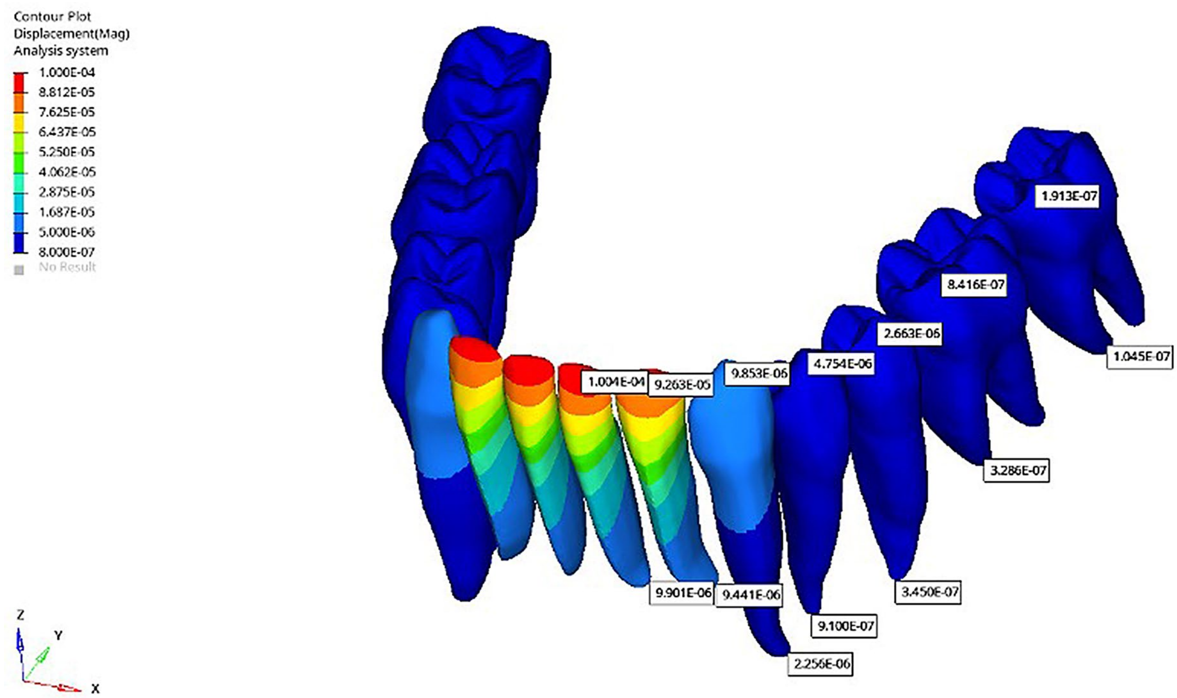

Fig. 14 FEA image of the total displacement of the Model 11

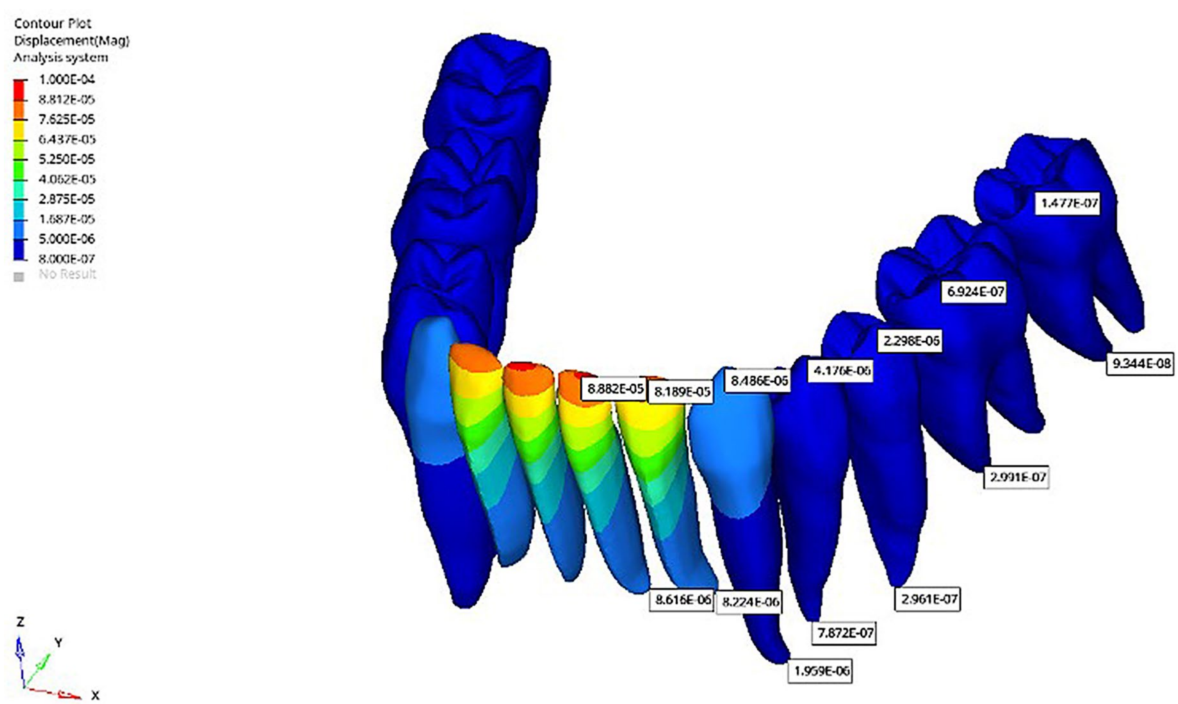

Fig. 15 FEA image of the total displacement of the Model 12

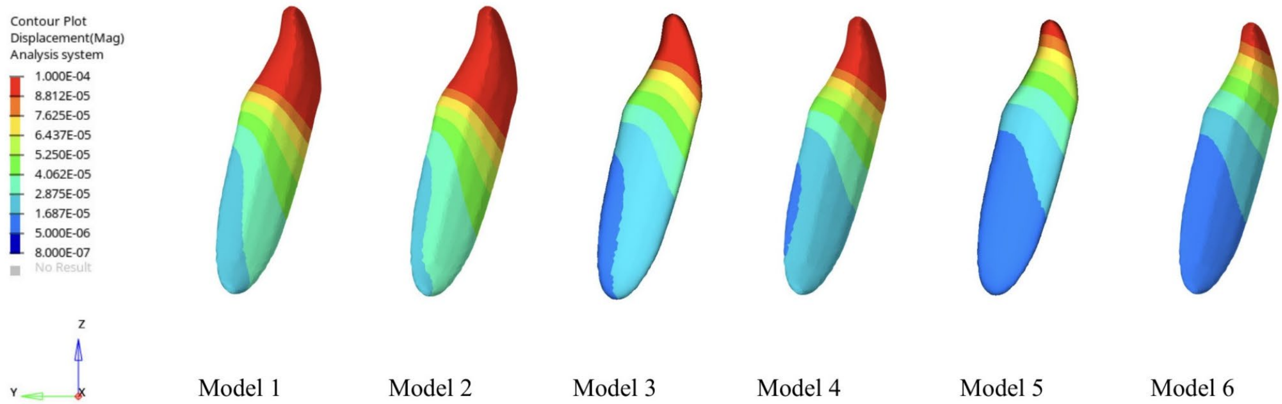

Fig. 16 FEA views of the total displacement in models using MBT brackets

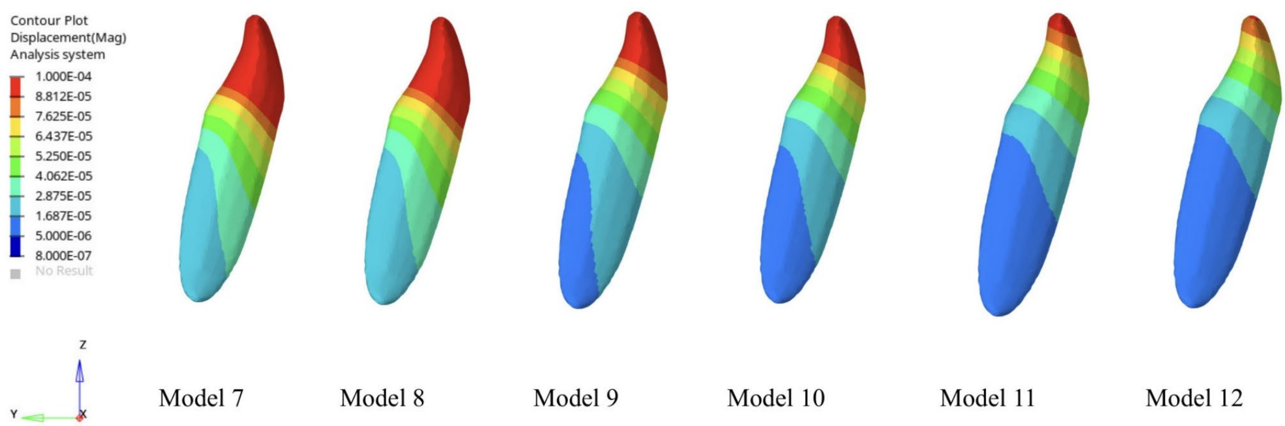

Fig. 17 FEA views of the total displacement in models using Roth brackets

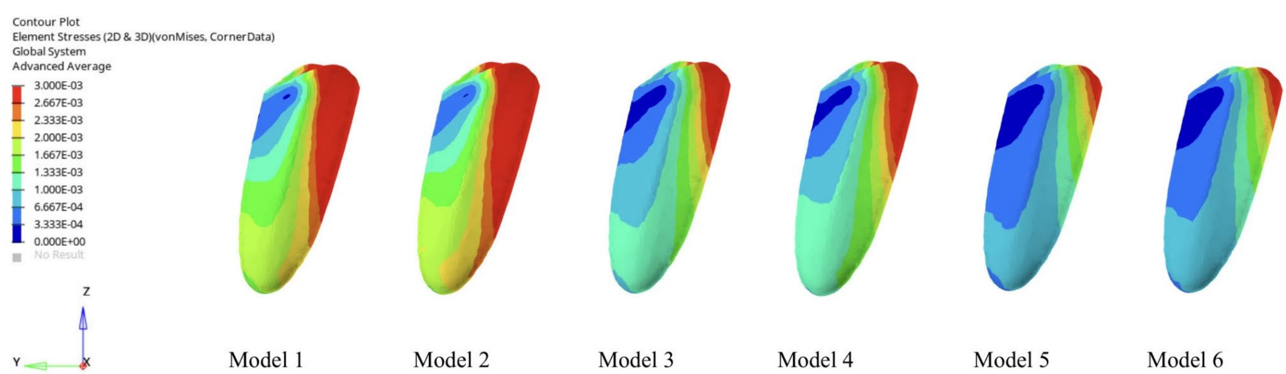

Fig. 18 The FEA views illustrate the von Mises stresses occurring in the PDL models with MBT brackets

of all, showed the lowest PDL stress values, with 3.460E-03 MPa for the central incisors and 2.897E-03 MPa for the lateral incisors.

Comparison of Von Mises stress distribution in models with 0.022 slot MBT brackets

The FEA images illustrate the Von Mises stress distribution in Models 1 to 6, where the color gradient represents stress intensity on the lower incisors (Fig. 18). Model 1 and Model 2 exhibit the highest stress concentration, particularly in the incisal and cervical regions, suggesting that these models generate greater forces on the lower incisors, increasing the risk of PDL stress. Model 3 and Model 4 show moderate stress levels, with reduced intensity compared to the first two models, indicating a more controlled force application. Model 5 and Model

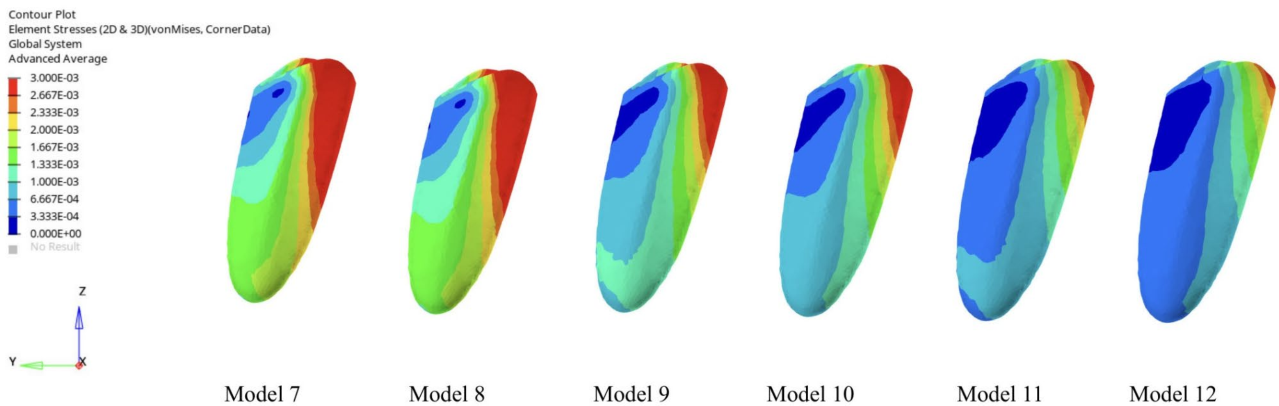

Fig. 19 The FEA views illustrate the von Mises stresses occurring in the PDL models with Roth brackets

6 present the lowest stress levels, with blue-dominated regions, suggesting minimal force impact, leading to a safer and more stable orthodontic force application.

Comparison of Von Mises stress distribution in models with 0.018 slot Roth brackets

The FEA images illustrate the Von Mises stress distribution in Models 7 to 12, with a color gradient representing stress intensity on the lower incisors (Fig. 19). Model 7 and Model 8 exhibit the highest stress concentration, particularly in the incisal and cervical areas, indicating that these models generate stronger forces on the lower incisors. Model 9 and Model 10 show moderate stress levels, suggesting a more balanced force application with less risk of excessive stress on the PDL. Model 11 and Model 12 present the lowest stress levels.

Comparison across models

Models 1, 2, 7, and 8 are the most aggressive in terms of both displacement and PDL stress.

Models 3, 4, 9, and 10 offer moderate force distribution, making them more balanced options.

Models 5, 6, 11, and 12 are the most conservative, prioritizing stability, reduced stress, and safer biomechanics.

Discussion

In orthodontic treatment, understanding the forces that affect tooth movement and stress distribution is critical for creating effective and safe treatment plans. The objective of this study is to analyze the forces applied by reverse curve of spee archwires with different depths and dimensions in both Roth and MBT-type brackets. Our findings reflect that the force generated by the wire-bracket combination plays a significant role in determining the displacement of teeth and the resulting stress on the PDL.

The results of this study further highlight the biomechanical differences between Roth and MBT bracket systems. Roth brackets, known for their precision and emphasis on overcorrection of deep bites, demonstrated higher force outputs in Models 7 and 8. These findings align with the Roth system's design, which aims to flatten the curve of Spee by applying stronger forces to the molars and premolars, leading to significant vertical and anteroposterior movement. This system is often preferred in cases where deep bite correction is the primary goal. In contrast, the MBT system, which is designed to apply lighter forces with more gradual tooth movement, demonstrated more conservative outcomes in Models 5 and 6.

Another parameter we assessed in this study was slot width. 0.022" slot offers more freedom for movement for initial aligning archwires within the relatively larger slot, theoretically resulting in lighter aligning forces. Accommodates larger working archwires, such as 0.019" x 0.025" wires, which are effective for space closure and controlling overbite. 0.018" slot provides improved torque control, particularly in the anterior teeth, due to a tighter fit with typical finishing archwires like 0.016" x 0.022" or 0.017" x 0.025", especially in the finishing stages. Scientific evidence supports many of these points. Ultimately, the choice between slot sizes depends on the clinician's familiarity with each system's strengths and limitations [20].

In our study, we used 0.22" slot MBT brackets and 0.18" slot Roth brackets because they are the most commonly used prescriptions. According to a study, 52.6% of orthodontists prefer MBT brackets, whereas 44% orthodontists prefer Roth brackets [21]. Regarding the most frequently used bracket slot sizes, 80.9% of orthodontists prefer 0.22" slot brackets, while 8.6% use 0.18" slot brackets. The remaining 10.5% of orthodontists use both types of bracket slots. According to several studies, Yassir et al. [22] and El-Angbawi et al. [23] evaluated the effectiveness of 0.018-inch and 0.022-inch slot MBT bracket systems in terms of treatment duration, outcomes, and effects. Their findings indicated no significant difference between the two slot sizes regarding occlusal outcome quality (as measured by Peer Assessment Rating score reduction), changes in incisor inclination, patient perception of treatment, or the occurrence of orthodontically induced inflammatory root resorption. Mittal et al. [24] conducted a randomized controlled trial to examine the impact of bracket prescription on treatment outcomes. They performed the study using 20 Roth and 20 MBT brackets with the same slot size. The study compared Roth and MBT brackets based on the Incisor and Canine Aesthetic Torque and Tip scores. Results indicated no statistically significant difference in the final inclination of the anterior teeth ($p = 0.132$). Similar to our study, this research was also conducted on non-extraction cases. In light of these studies, we selected a 0.022" slot width for MBT brackets and a 0.018" slot width for Roth brackets in our study. A total of six models were created for each bracket group, allowing for comparisons within each system regarding the effects of the wires used. Additionally, the impact of the thickest wire applicable for each bracket type on the teeth could be analyzed, providing further insight into their biomechanical effects.

In our finite element model, the deepest point of the Curve of Spee (COS) was 2.4 mm, which is considered within the normal range by some authors [25, 26]. However, some researchers says spee depth up to 2 mm considered as normal [8]. Koyama pointed out that deepest point of the curve of spee is typically located at the midpoint, around the second premolar [27] whereas some authors observed that it often aligns with the mesio-buccal cusp of the lower first molar [8, 28, 29]. In our study, the deepest point of the curve of spee in mandibular model designed 2.4 mm, as suggested by Koyama.

In this study, Models 1, 2, 7, and 8 which represent more aggressive force applications with larger wire dimensions and depths, showed the highest levels of tooth displacement and PDL stress. These findings correlate with the application of reverse curve archwires, which are often use to correct deep bites. In particular, 0.022 slot MBT brackets with 0.019×0.025" and 0.021×0.025" wires and 0.018 slot Roth brackets with 0.017×0.025" and 0.016×0.022" wires generated forces that resulted in the highest levels of displacement for the central incisors and significant stress in the PDL. These aggressive forces can be useful for correcting severe malocclusions or deep bite cases. However, series of studies has shown that stress/ strain on the PDL are linked to tissue necrosis and hyalinization, emphasizing the need to keep PDL stress within an optimal range. Excessive pressure can lead to PDL occlusion, impaired function, and bone resorption [30, 31].

In contrast, Models 5, 9, 10, 11, and 12 demonstrated more conservative force applications. These models, featuring MBT and Roth brackets with smaller wire dimensions (e.g., 0.017×0.025" and 0.016×0.022") and shallower wire depths (e.g., 20 mm and 25 mm), resulted in significantly lower tooth displacement and PDL stress. For instance, Model 11, which applied the lowest forces, exhibited minimal displacement and the least amount of stress on the PDL. This conservative approach is particularly beneficial in cases requiring slow, controlled tooth movement, such as during the finishing stages of treatment or in patients with fragile periodontal conditions.

Currently, the influence of orthodontic treatment on root resorption is not fully understood due to its complex, multifactorial causes, which likely include individual biological factors, genetic susceptibility, and mechanical stress [32, 33]. Root resorpsion can impact long-term dental health, and studies have shown that patients undergoing orthodontics often experience more severe root shortening [34, 35]. Both of the light forces and heavy continuous forces in orthodontic treatment found that produced root resorpsion, although heavy forces were associated with greater resorption [32, 36, 37]. Studies concluded that higher forces resulted in substantially more root resorption compared to lighter forces [32, 36–38]. Researchs using scanning electron microscopy (SEM) has shown that root resorption is influenced by both the duration and magnitude of the applied force, and that the type of tooth movement [39, 40]. As the vertical type of movements (intrusion and extrusion) most closely associated with external apical root resorption [41, 42]. Han et al. observed that root resorption caused by extrusive forces did not differ significantly from the control group, while intrusive forces led to a notable increase in the percentage of resorbed root area [43]. According to the study by Harris et al., as the magnitude of the intrusive force increases, root resorption also increases [32].

Light continuous forces tend to produce more physiological tooth movement, reducing the risk of root resorption and maintaining the integrity of the surrounding bone and PDL [44]. This approach is also consistent with the findings of our study, as the models with lighter forces showed a more balanced stress distribution, making them ideal for maintaining long-term periodontal health.

One of the strengths of this study is the use of FEA to assess the effects of orthodontic forces on tooth movement and stress distribution. If we know the mechanical properties of a material, determining stresses becomes straightforward. With finite element analysis, forces applied in different directions and the resulting stresses can be calculated [45].

Numerous studies in dentistry have studied the FEA Williams and Edmundson used FEA to study the rotation center of the maxillary central tooth, finding that it is insensitive to the elastic properties of PDL and independent of applied force [46]. Tanne and colleagues investigated the stress on roots, alveolar bone, and PDL, observing irregular stresses along the root during tipping movements. They compared stresses around the tooth root generated by translation and tipping using FEA [47].

In further research, Vasquez and others analyzed a model with an endosseous implant and PDL using FEM, finding that frictionless systems with T-loops are preferable for minimizing stress when the anchorage unit includes an implant [48].Geramy examined stress components in the PDL under horizontal and vertical forces and found that alveolar bone loss increases stress production compared to healthy bone support, especially in the PDL's cervical area during tipping [13].

Although FEA studies have been conducted on various topics in orthodontics, there are no studies similar to ours that focus on reverse curve wires. Furthermore, no other research compares wires of different depths or evaluates the commonly used MBT and Roth brackets in treatment. In this context, our study stands out as a unique and valuable addition to the literature in the field. There are no studies investigating the effects of both MBT and Roth brackets on the dentition during the leveling of the curve of Spee, either through clinical research or finite element analysis. However, some studies have examined the general effects of flattening the curve of Spee. Pandis et al. [49] aimed to analyze the impact of leveling the curve of Spee on the inclination of mandibular incisors and the width of the mandibular arch. The primary factor influencing COS flattening was the lower incisor to mandibular plane angle. It was found that for every 1 mm of COS leveling, the mandibular incisors proclined by 4 degrees, without an increase in arch width. Another study examined the effects of different archwires on blood flow (BF) changes during curve of Spee (COS) leveling. Thirty subjects with COS > 5 mm were divided into three groups using different archwires: 0.017 × 0.025-inch stainless steel (SS), 0.019 × 0.025-inch SS, and 0.021 × 0.025-inch β-titanium (TMA), all with a 5 mm reverse COS. BF was measured using a laser Doppler flowmeter. BF decreased 20 min after force application but returned to baseline within a week. Premolars showed greater BF reduction than incisors, and intrusive forces had a lower negative impact. The study highlights the importance of selecting forces that minimize BF disruption during COS leveling [50]. A different study developed and tested a dynamic in vitro photo-elastic model to evaluate the effects of orthodontic mechanics on a full mandibular arch. The model consisted of a mandibular arch with teeth embedded in a gelatin-based material that allowed tooth movement in response to orthodontic forces while providing excellent photo-elastic properties for stress distribution analysis around the roots. Using this model, researchers examined the effects of increasing the reverse curve of Spee in a 0.018 × 0.025-inch stainless steel archwire. The findings showed that a 1-mm reverse curve of Spee increased arch length by 1.6 mm, but further increasing the reverse curve to 5 mm did not lead to additional arch lengthening. Photo-elastic analysis also revealed that as the reverse curve of Spee increased, stress distribution intensified around the roots of the incisors and molars.

The limitations of this method are boundary conditions—such as the type of analysis (linear versus nonlinear) and material characteristics (isotropy versus anisotropy and elasticity versus plasticity) as well as the precision of input data, including the anatomical accuracy of models reconstructed from radiologic data [7, 11, 12, 51].

Another limitation of this study is that teeth typically undergo leveling and alignment during the first stage of treatment. However, in our study, archwires were applied to mandibular teeth with a 2.4 mm deep curve of Spee without leveling and alignment stage. Similarly, Nasrawi et al. [52] in their finite element analysis study, stated that they used archwires of different sizes based on bracket slot dimensions, such as 0.017 × 0.025-in SS, 0.019 × 0.025-in SS, and 0.021 × 0.025-in TMA for leveling the curve of Spee. In future studies, two-stage modeling can be conducted to include the leveling sequence followed by the flattening of the curve of Spee. By developing more realistic models, this research can be expanded to provide better guidance for clinicians.

However, it is important to note that FEA is a simulation-based tool, and while it provides valuable insights into the biomechanics of orthodontic treatment, it may not fully replicate the complexities of biological systems. For instance, individual variations in bone density, tooth morphology, and PDL thickness can affect the real-life outcomes of orthodontic treatments [11, 53]. Therefore, future studies should incorporate clinical trials to validate the findings of FEA-based research and assess their applicability in real-world settings.

The results of this study understand the importance of individualized treatment planning in orthodontics. While aggressive force applications may be necessary in certain cases, particularly in patients with severe malocclusions or deep bites, the potential risks associated with high PDL stress and tooth displacement cannot be ignored. Conversely, more conservative force applications offer a safer alternative for patients with sensitive periodontal conditions or those in the final stages of treatment. These models allow for controlled, gradual tooth movement, minimizing the risk of root resorption and preserving the integrity of the PDL. The study findings demonstrate that higher force applications, particularly in Models 1, 2, 7, and 8, resulted in greater PDL stress and increased tooth displacement. This aligns with clinical observations where excessive force application can contribute to root resorption, tissue necrosis, and prolonged treatment times. On the other hand, Models 5, 9, 10, 11, and 12, which applied lighter forces, led to lower PDL stress, allowing for safer and more controlled tooth movement while reducing the risk of root damage. Clinicians may sometimes use deeper reverse curve archwires to accelerate treatment progress. However, they must consider the potential side effects that may arise as a result of this approach. When evaluating patients, factors such as bone structure, lower incisor inclinations and the periodontal condition surrounding the lower incisors—including the presence of dehiscence, fenestrations, and mobility—should be carefully assessed. If clinicians choose to use models that generate higher forces, as seen in our study, they should be mindful of the associated risks and take preventive measures to minimize adverse effects.

Conclusion

In conclusion, this study provides valuable insights into the biomechanical effects of reverse curve archwires with varying dimensions and depths on tooth movement and PDL stress. The findings highlight the importance of selecting the appropriate wire-bracket combination based on the specific needs of the patient, ensuring that orthodontic forces are applied in a way that maximizes treatment effectiveness while minimizing the risk of periodontal damage such as root resorption. As FEA continues to evolve as a tool for orthodontic research, it will play an increasingly important role in helping clinicians optimize treatment plans and improve patient outcomes.

Future research should focus on further exploring the long-term effects of different wire-bracket combinations, particularly in relation to relapse rates and post-treatment occlusal stability. Additionally, future studies can focus on long-term clinical trials to evaluate the effects of different reverse curve archwires on root resorption, periodontal health, and treatment stability. Incorporating patient-specific finite element analysis (FEA) models based on CBCT scans can enhance accuracy in predicting stress distribution and tooth movement. Artificial intelligence and machine learning can also be integrated to develop personalized treatment protocols, optimizing force application based on bone density, incisor inclination, and periodontal conditions.

Abbreviations

FEA Finite Element Analysis
PDL Periodontal Ligament
COS Curve Of Spee
BF Blood Flow

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Author contributions

SY collected the data and did the research. SY, EM and KH wrote the paper together. All authors read and approved the final manuscript.

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Data availability

The data underlying this article cannot be shared publicly due to ethical concerns (for the privacy of individuals that participated in the study). The data will be shared on reasonable request to the corresponding author.

Declarations

Ethics approval and consent to participate

This study was conducted in Faculty of Dentistry at Biruni University. The study received approval by the Biruni University Ethics Committee (Decision no: 2023/85 – 10). This study was carried out as part of a PhD thesis.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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References

1. Spee FG, Biedenbach MA, Hotz M, Hitchcock HP. The gliding path of the mandible along the skull. J Am Dent Association. 1980;100(5):670–5.
2. Graber TM. Orthod Principles Pract Growth Dev. 1972;27:128.
3. Roth R. The straight-wire appliance 17 years later. J Clin Orthodontics: JCO. 1987;21(9):632–42.
4. McLaughlin RP, Bennett JC, Trevisi HJ. Systemized orthodontic treatment mechanics. 2001.
5. Proffit WR, Fields HW Jr, Sarver DM. Contemporary orthodontics: Elsevier Health Sciences; 2006.
6. Baratam S, Sreedhar C. Deep overbite—A review (Deep bite, deep overbite, excessive overbite). Ann Essences Dent. 2009;1(1):8–25.
7. Mahmood Ghuloom KH, Mascarenhas R, Parveen S, Husain A. Finite element analysis of orthodontically induced stress in the periodontal ligament of the maxillary first molar with simulated bone loss. J Comput Methods Sci Eng. 2017;17(2):243–52.
8. Li Y, Jacox LA, Little SH, Ko C-C. Orthodontic tooth movement: the biology and clinical implications. Kaohsiung J Med Sci. 2018;34(4):207–14.
9. Feller L, Khammissa R, Schechter I, Thomadakis G, Fourie J, Lemmer J. Biological events in periodontal ligament and alveolar bone associated with application of orthodontic forces. Sci World J. 2015;2015(1):876509.
10. Jain M, Varghese J, Mascarenhas R, Mogra S, Shetty S, Dhakar N. Assessment of clinical outcomes of Roth and MBT bracket prescription using the American board of orthodontics objective grading system. Contemp Clin Dent. 2013;4(3):307–12.
11. Jeon PD, Turley PK, Moon HB, Ting K. Analysis of stress in the periodontium of the maxillary first molar with a three-dimensional finite element model. Am J Orthod Dentofac Orthop. 1999;115(3):267–74.
12. Jeon PD, Turley PK, Ting K. Three-dimensional finite element analysis of stress in the periodontal ligament of the maxillary first molar with simulated bone loss. Am J Orthod Dentofac Orthop. 2001;119(5):498–504.
13. Geramy A. Alveolar bone resorption and the center of resistance modification (3-D analysis by means of the finite element method). Am J Orthod Dentofac Orthop. 2000;117(4):399–405.
14. Kusy R, Whitley J. Coefficients of friction for arch wires in stainless steel and polycrystalline alumina bracket slots. I. The dry state. Am J Orthod Dentofac Orthop. 1990;98(4):300–12.
15. Harikrishnan P, Magesh V, Ajayan AM, JebaSingh DK. Finite element analysis of torque induced orthodontic bracket slot deformation in various bracket-archwire contact assembly. Comput Methods Programs Biomed. 2020;197:105748.

16. Hasan LA, Al Qassar SSS, Alrawi MN, Alhajar EH. Does the flatting of the curve of Spee affect the chewing force distribution in the mandible?(3D finite element study). J Orthodontic Sci. 2021;10(1):1.
17. Hsu M-L, Chang C-L. Application of finite element analysis in dentistry. Finite Elem Anal. 2010;5:43–6.
18. Choi A, Ben-Nissan B, Conway R. Three-dimensional modelling and finite element analysis of the human mandible during clenching. Aust Dent J. 2005;50(1):42–8.
19. Kim K-N, Cha B-K, Choi D-S, Jang I, Yi Y-J, Jost-Brinkmann P-G. A finite element study on the effects of midsymphyseal distraction osteogenesis on the mandible and articular disc. Angle Orthod. 2012;82(3):464–71.
20. Carcara S, Preston CB, Jureyda O. The relationship between the curve of Spee, relapse, and the Alexander discipline. Seminars in orthodontics: 2001. Elsevier; 2001. pp. 90–9.
21. BalDaS LF, FaLEh aLFaLEh L. Orthodontic diagnostic tools and material usage among orthodontists in Saudi Arabia. Europe, 50:2329.
22. Yassir YA, El-Angbawi AM, McIntyre GT, Revie GF, Bearn DR. A randomized clinical trial of the effectiveness of 0.018-inch and 0.022-inch slot orthodontic bracket systems: part 2—quality of treatment. Eur J Orthod. 2019;41(2):143–53.
23. El-Angbawi AM, Yassir YA, McIntyre GT, Revie GF, Bearn DR. A randomized clinical trial of the effectiveness of 0.018-inch and 0.022-inch slot orthodontic bracket systems: part 3—biological side-effects of treatment. Eur J Orthod. 2019;41(2):154–64.
24. Mittal M, Thiruvenkatachari B, Sandler PJ, Benson PE. A three-dimensional comparison of torque achieved with a preadjusted Edgewise appliance using a Roth or MBT prescription. Angle Orthod. 2015;85(2):292–7.
25. Baydaş B, Yavuz İ, Atasaral N, Ceylan İ, Dağsuyu İM. Investigation of the changes in the positions of upper and lower incisors, overjet, overbite, and irregularity index in subjects with different depths of curve of Spee. Angle Orthod. 2004;74(3):349–55.
26. Ahmed I, Nazir R, Ahsan T. Influence of malocclusion on the depth of curve of Spee. JPMA J Pakistan Med Association. 2011;61(11):1056–9.
27. KOYAMA T. A comparative analysis of the curve of Spee (lateral aspect) before and after orthodontic treatment with particular reference to overbite patients. J Nihon Univ Sch Dent. 1979;21(1–4):25–34.
28. Lie F, Kuitert R, Zentner A. Post-treatment development of the curve of Spee. Eur J Orthod. 2006;28(3):262–8.
29. Surendran SV, Hussain S, Bhoominthan S, Nayar S, Jayesh R. Analysis of the curve of Spee and the curve of Wilson in adult Indian population: A three-dimensional measurement study. J Indian Prosthodontic Soc. 2016;16(4):335–9.
30. Hohmann A, Wolfram U, Geiger M, Boryor A, Kober C, Sander C, Sander FG. Correspondences of hydrostatic pressure in periodontal ligament with regions of root resorption: a clinical and a finite element study of the same human teeth. Comput Methods Programs Biomed. 2009;93(2):155–61.
31. Choy K, Pae E-K, Park Y, Kim K-H, Burstone CJ. Effect of root and bone morphology on the stress distribution in the periodontal ligament. Am J Orthod Dentofac Orthop. 2000;117(1):98–105.
32. Harris EF, Robinson QC, Woods MA. An analysis of causes of apical root resorption in patients not treated orthodontically. Quintessence Int 1993, 24(6).
33. Killiany DM. Root resorption caused by orthodontictreatment: an evidence-based review of literature. Seminars in orthodontics: 1999. Elsevier; 1999. pp. 128–33.
34. Stenvik A, Mjo I. Pulp and dentine reactions to experimental tooth intrusion: a histologic study of the initial changes. Am J Orthod. 1970;57(4):370–85.
35. KD M. Quantitative determination of root resorption during orthodontic treatment. Am J Orthod. 1964;50:143.
36. Barbagallo LJ, Jones AS, Petocz P, Darendeliler MA. Physical properties of root cementum: part 10. Comparison of the effects of invisible removable thermoplastic appliances with light and heavy orthodontic forces on premolar cementum. A microcomputed-tomography study. Am J Orthod Dentofac Orthop. 2008;133(2):218–27.
37. Chan EK, Darendeliler MA. Exploring the third dimension in root resorption. Orthod Craniofac Res. 2004;7(2):64–70.
38. Chan E, Darendeliler MA. Physical properties of root cementum: part 7. Extent of root resorption under areas of compression and tension. Am J Orthod Dentofac Orthop. 2006;129(4):504–10.
39. Casa MA, Faltin RM, Faltin K, Sander F-G, Arana-Chavez VE. Root resorptions in upper first premolars after application of continuous torque moment Intra-Individual study: Intra-Individual study. J Orofac Orthopedics/Fortschritte Der Kieferorthopädie. 2001;62:285–95.
40. Faltin RM, Arana-Chavez VE, Faltin K, Sander F-G, Wichelhaus A. Root resorptions in upper first premolars after application of continuous intrusive forces. Intra-individual study. J Orofac Orthop = Fortschr Der Kieferorthopadie: Organ/official J Dtsch Gesellschaft fur Kieferorthop. 1998;59(4):208–19.
41. Parker RJ, Harris EF. Directions of orthodontic tooth movements associated with external apical root resorption of the maxillary central incisor. Am J Orthod Dentofac Orthop. 1998;114(6):677–83.
42. Xu T, Baumrind S. The relationship between apical root resorption and orthodontic tooth movement in growing subjects. Zhonghua Kou Qiang Yi Xue Za zhi = Zhonghua Kouqiang Yixue Zazhi = Chin J Stomatology. 2002;37(4):265–8.
43. Han G, Huang S, Von den Hoff JW, Zeng X, Kuijpers-Jagtman AM. Root resorption after orthodontic intrusion and extrusion: an intraindividual study. Angle Orthod. 2005;75(6):912–8.
44. Yee JA, Türk T, Elekdağ-Türk S, Cheng LL, Darendeliler MA. Rate of tooth movement under heavy and light continuous orthodontic forces. Am J Orthod Dentofac Orthop. 2009;136(2):150. e151-150. e159.
45. Bica C, Brezeanu L, Bica D, Suciu M. Biomechanical reactions due to orthodontic forces. A finite element study. Procedia Technol. 2015;19:895–900.
46. Williams K, Edmundson J. Orthodontic tooth movement analysed by the finite element method. Biomaterials. 1984;5(6):347–51.
47. Tanne K, Koenig HA, Burstone CJ. Moment to force ratios and the center of rotation. Am J Orthod Dentofac Orthop. 1988;94(5):426–31.
48. Vasquez M, Calao E, Becerra F, Ossa J, Enríquez C, Fresneda E. Initial stress differences between sliding and sectional mechanics with an endosseous implant as Anchorage: a 3-dimensional finite element analysis. Angle Orthod. 2001;71(4):247–56.
49. Pandis N, Polychronopoulou A, Sifakakis I, Makou M, Eliades T. Effects of levelling of the curve of Spee on the proclination of mandibular incisors and expansion of dental arches: a prospective clinical trial. Australasian Orthodontic J. 2010;26(1):61–5.
50. Ba-Hattab R, Abu Alhaija ES, Nasrawi YH, Taha N, Daher H, Daher S. Leveling the curve of Spee using different sized archwires: a randomized clinical trial of blood flow changes. Clin Oral Invest. 2023;27(6):2943–55.
51. Moga R-A, Cosgarea R, Buru SM, Chiorean CG. Finite element analysis of the dental pulp under orthodontic forces. Am J Orthod Dentofac Orthop. 2019;155(4):543–51.
52. Nasrawi YH, Alhaija ESA, Al Maaitah EF. Efficacy of lower arch leveling, lower incisors' root resorption, and pain associated with the correction of curve of Spee using different orthodontic archwires: a randomized clinical trial. Clin Oral Invest. 2022;26(12):7107–20.
53. Hemanth M, Raghuveer H, Rani M, Hegde C, Vedavathi B. Stress induced in the periodontal ligament under orthodontic loading (part I): a finite element method study using linear analysis. J Int Oral Health: JIOH. 2015;7(8):129.

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