

ORIGINAL RESEARCH

Evaluation of retracted anterior teeth with varying crown-to-root ratios via clear aligner therapy: a finite element study

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Abstract

Background: In orthodontic treatment for bimaxillary protrusion, tooth extraction is often required. This study analyzed tooth displacement trends and stress distribution during clear aligner therapy in normal-root and short-root groups. **Methods:** Three-dimensional finite element models (FEMs) were constructed. The normal-root group had maxillary central incisors with 14 mm root lengths, whereas the short-root group had 7.6 mm root lengths. Both groups had 10 mm crown lengths. Three movement conditions were simulated: including C1: overall retraction of the maxillary anterior teeth by 0.2 mm; C2: distal movement of the maxillary canines to 1/3 of the extraction space, followed by 0.2 mm retraction of the maxillary central incisors; and C3: complete distal movement of the maxillary canines prior to 0.2 mm retraction of the maxillary central incisors. Molars served as anchorage units. **Results:** The maxillary central incisors showed the lowest von Mises stress and hydrostatic pressure under condition C1. Condition C2, in contrast, resulted in the highest hydrostatic pressure. Across all conditions, stress concentration was consistently found in the cervical regions of both the anterior and anchorage teeth. Under C1, displacement in both the X-axis (mesiodistal) and Z-axis (vertical) directions was the largest, indicating a stronger tendency for mesial crown movement and intrusive displacement of the teeth. Under C1, von Mises stress of the root was the highest, while hydrostatic stress was the lowest. **Conclusions:** Compared to the normal-root group, the short-rooted anterior teeth responded more favorably to overall retraction (C1). However, enhanced posterior anchorage is essential to manage the increased stress in these cases.

Keywords

Finite element models; Short-root anomaly; Clear aligner therapy; Bimaxillary protrusion; Extraction

1. Introduction

Lind [1] defined the hallmark of short-rooted teeth as abnormal root morphology and reduced tooth length, typically characterized by a root-to-crown (R/C) ratio $\leq 1:1$. This condition may lead to compromised periodontal attachment, increased risk of periodontal disease, and even premature tooth loss, ultimately affecting masticatory function and facial aesthetics. Short root anomaly (SRA) most commonly affects the maxillary central incisors, followed by the maxillary premolars, maxillary lateral central incisors, and mandibular premolars, while the lowest incidence is observed in canines and molars [2].

The etiology of SRA has been associated with various factors, including dental trauma, smoking during pregnancy, as well as several genetic and congenital syndromes such as Turner syndrome, Fraser syndrome, Hallermann-Streiff syndrome, and Schimke immuno-osseous dysplasia [3–6]. Additionally, metabolic disorders—such as

hypophosphatemia, pseudohypoparathyroidism, and vitamin D-dependent rickets—have been implicated. Patients with severe Cooley's anemia have also been reported to exhibit shortened roots [7]. SRA can also occur in individuals without systemic conditions, suggesting a multifactorial pathogenesis. It has been linked to deficiencies in several key regulatory factors and proteins involved in tooth development, including Sequence similarity 20 member A (FAM20A), β -catenin, bone morphogenetic proteins (BMPs), nuclear factor I-C (Nfic), Dickkopf-related protein 1 (DKK1), and transforming growth factor-beta (TGF- β) [8]. Numerous studies indicate that the prevalence of SRA varies across different populations. In Chinese people, the prevalence was reported at 2.7%, with SRA primarily affecting maxillary central incisors (83.72%) and premolars (16.28%). Similarly, in orthodontic patient samples—particularly among Hispanic individuals—the prevalence approaches 10% in central incisor. Furthermore,

SRA appears to be nearly three times more prevalent in females than in males [9–11].

During orthodontic treatment, varying degrees of root resorption are frequently observed, with an incidence as high as 91%, and it can occur in any tooth position [12]. Anterior teeth are more susceptible to root resorption than posterior teeth [13]. Among anterior teeth, the maxillary central incisors are the most vulnerable, with incidence rates ranging from 47% to 95% [14]. However, current domestic research on the incidence of SRA—whether in fixed orthodontics or clear aligners—remains limited. Clear aligners have gained significant popularity among patients in recent years. Modern aligner systems are now capable of effectively addressing not only simple crowding but also increasingly complex extraction cases [15]. Moreover, aligners have been reported to minimize dental trauma, apical resorption, and microbial risk. Their light and continuous orthodontic forces are perceived by the periodontium as intermittent, which may allow for orthodontic tooth movement with reduced cell damage in the periodontal tissues [16–19]. In conventional orthodontic treatment, the selection of retraction method in extraction cases is typically based on the required amount of retraction and the strength of anchorage control. However, for SRA patients, additional considerations must be given to the stress placed on the maxillary anterior teeth and the selection of posterior anchorage.

Research by Cutrera's *et al.* [10] showed that the maxillary left central incisor in the SRA group exhibited significantly less proportional and non-proportional loss in tooth length during orthodontic treatment. Early studies also suggested that SRA is genetically determined and emphasized the need for modified clinical and radiographic protocols to minimize orthodontic damage in these patients [20]. Despite these insights, detailed clinical guidance on orthodontic treatment for patients with SRA remains scarce. Therefore, the purpose of this study is to compare those with short roots to those with normal root lengths. By analyzing the displacement trends and stress distribution under different tooth movement patterns during clear aligner therapy, we aim to identify a more suitable retraction strategy for SRA patients. The findings may help reduce orthodontic risks in patients and improve treatment outcomes in this patient population.

2. Materials and methods

2.1 Original 3D model established

This research was started from April 2024 and was finished in August 2024. Cone-beam computed tomography (CBCT, 3D eXam, KAVO, Hatfield, PA, USA) data was obtained from a 14-year-old female patient. She had a healthy craniofacial structure, complete dentition, and Class I occlusion. The scan had been acquired for treatment purposes. As adolescence is considered an optimal period for orthodontic treatment, and to minimize ethical concerns, the patient's data were selected for this study. The treatment plan involved extraction of the first premolars and subsequent anterior tooth retraction with strong anchorage. A three-dimensional model of the patient's maxillary bone, dentition, and surrounding periodontal tissues was established. An additional model was created: the crown-

to-root ratio of the maxillary central incisors was set to 1:0.54 to simulate short-rooted anatomy. Simulated aligner loads were applied under three working conditions: C1: overall retraction of the maxillary anterior teeth by 0.2 mm; C2: distal movement of the maxillary canines to 1/3 of the extraction space, followed by retraction of the maxillary central incisors by 0.2 mm; C3: complete distal movement of the maxillary canines first, followed by retraction of the maxillary central incisors by 0.2 mm.

The CBCT data were imported into Mimics 20.0 (Materialise Software, Leuven, Belgium). Geomagic Studio 2014 (Raindrop Geomagic, Rock Hill, NC, USA) and NX1911 software (Siemens PLM, Nuremberg, BY, Germany). The models included the maxilla, upper dentition, periodontal ligament, alveolar bone, and aligners. The right side of the maxillary model was mirrored to create bilateral symmetry. Ansys Workbench 2019 (Ansys, Inc., Canonsburg, PA, USA) was used to analyze six scenarios of the orthodontic model for this extraction case, exploring the displacement trends of the maxillary teeth, stress levels, and the distribution of stress in the periodontal ligament.

2.2 Coordinate systems design & material property

We defined the boundary conditions as follows: the upper border of the maxilla and the sinus opening were constrained and fixed. Teeth were set as free bodies. In this study model, there were 21 objects. The contact between the periodontal ligament and cortical bone was Bonded Type, it meant that they were non-separable and didn't slide relative to each other. The contacts between crowns, aligners and the crown were of the frictional type. The friction coefficients were 0.2 and 0.18; a friction-based condition was established for the contact interfaces between the aligner and the tooth crown surface [21]. Notably, no frictional contact was defined between the surfaces of the two central incisors. A unified coordinate system and a local coordinate system were used to define the X, Y, and Z axes. The former was used to describe bone and bone point displacement, while the latter was used to describe the displacement trends of the teeth. The axes were defined as follows: X-axis: perpendicular to the sagittal plane, with the mesial direction being positive; Y-axis: perpendicular to the coronal plane, pointing toward the lingual side as positive; Z-axis: perpendicular to the horizontal plane [22], pointing toward the gingival side as positive (Fig. 1).

This study simulated the loading patterns of identical displacements in clear aligner therapy, focusing on the initial displacement, root stress, and periapical stress distribution for both normal and short-rooted teeth. Two key mechanical indicators—hydrostatic stress and von Mises stress—were utilized in the analysis. Hydrostatic stress served as an indicator for analyzing orthodontic tooth movement. The positive or negative value of hydrostatic stress indicated the stress state of the periodontal ligament being under tension or compression. The magnitude of hydrostatic stress in the periodontal ligament was associated with the risk of root resorption during orthodontic treatment [23]. Von Mises stress, on the other hand, integrated the effects of compressive, tensile, and sheared stresses

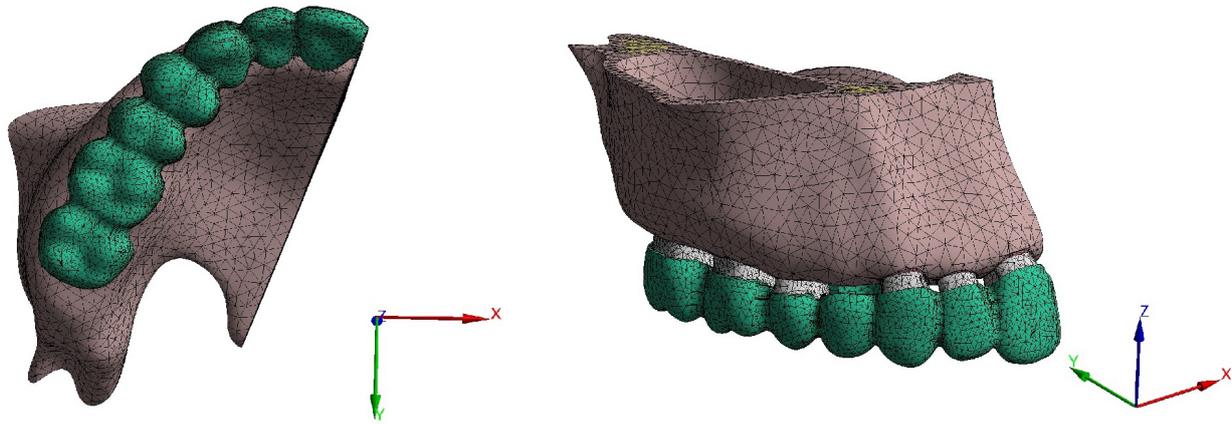


FIGURE 1. Coordinate axis position of the model. This model's mesh element type was 3D 10-node tetrahedrons. This figure showed the three-dimensional coordinate axis positions and the displacement tendencies within the model.

acting simultaneously at a given point within a material. It was widely used to identify the locations in a model that were susceptible to damage; specifically, the higher the von Mises stress value, the greater the likelihood of the model sustaining damage or failure [24]. Due to its comprehensive nature, von Mises stress was the most commonly employed analytical criterion in FEA. To facilitate modeling and reduce complexity, material properties and biological tissues were assumed to be idealized as isotropic, homogeneous, and nonlinearly elastic in this study. Material parameters [21, 25–27] were shown in Tables 1,2.

TABLE 1. Material properties used in the three-dimensional finite element model.

Material	Young's modulus (MPa)	Poisson's ratio
Cortex of bone	13,700	0.26
Cancellous bone	1370	0.30
Tooth	19,600	0.30
Periodontal ligament	0.143	0.45
Clear aligner	528	0.36

TABLE 2. Indicators to evaluate grid quality in the three-dimensional finite element model.

Ansys workbench	Max	Min	Average
Jacobian Ratio	1	3.22×10^{-2}	0.92128
Aspect Ratio	419.61	1.1785	2.6220
Maximum Corner Angle	177.89°	71.594°	103.5°
Skewness	0.99999	1.9×10^{-3}	0.3993

Max: maximum; Min: minimum.

2.3 Configuration setting

The loading design for the working conditions was detailed as follows: In all cases, the four first premolars were extracted,

and the anterior teeth were retracted using clear aligners with maximum anchorage, as illustrated in Fig. 2. Under the three working conditions (C1, C2, and C3), an additional 0.2 mm of retraction was applied to the clear aligners. No attachments were incorporated in the models for standardization purposes. The number of elements and nodes in all finite element models under different working conditions were shown in Tables 3,4.

3. Results

3.1 Movement and stress distribution of the central incisor

In both groups, the von Mises stress of the central incisor was lowest under C1 with the highest stress concentrated in the cervical area. The minimum hydrostatic pressure also occurred under C1. The central incisor showed the greatest retraction along the Y-axis under C1, with minimal displacement along the Z-axis, indicating the least amount of vertical compression. Notably, the elongation along the Z-axis in the short-root group was significantly greater than that of the normal-tooth group, as shown in Figs. 3,4.

3.2 The movement and the stress of the posterior teeth

For the second premolar, stress concentration was consistently located at the mesial root area. Under C1, the greatest displacement occurred in the X-axis and Z-axis directions, showing a prominent mesial and lingual movement of the crown. Although the short-root group showed slightly less displacement compared to the normal-root group, the difference was minor. The root experienced the highest von Mises stress and the lowest hydrostatic pressure. Additionally, in the normal-root group, a slight buccal inclination of the crown was observed along the Y-axis in C1, whereas in other conditions the crown inclined lingually. In contrast, the short-root group exhibited the greatest lingual inclination of the crown under C1 (Figs. 5,6).

Stress concentration in the first molar was observed at the cervical region in all groups. Under C1, displacement in both X- and Z-axes directions was greatest, with the crown showing

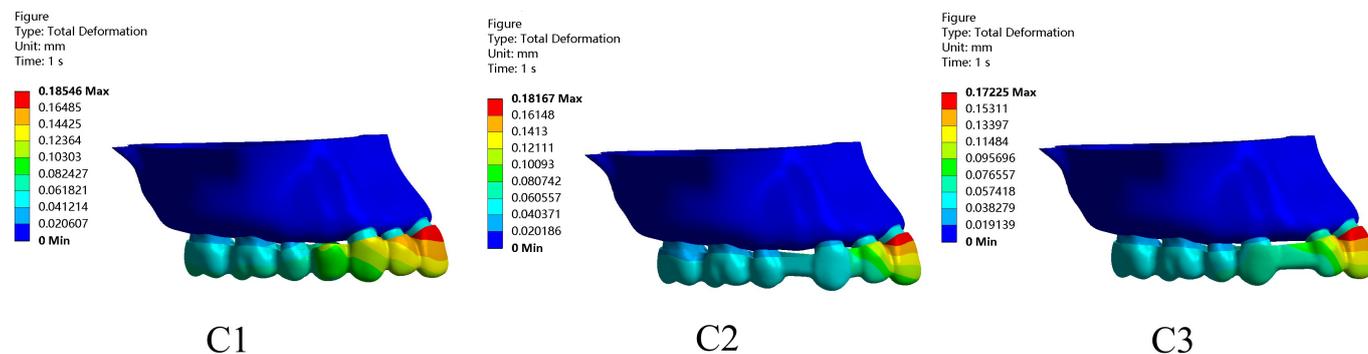


FIGURE 2. Three movement strategies. This figure showed three configuration settings. Max: maximum; Min: minimum.

TABLE 3. Mesh size used in the three-dimensional finite element model.

Material	Mesh size (mm)
Alveolar Bone	2.0
Periodontal ligament	0.5
Tooth	1.0
Clear aligner	1.0

TABLE 4. Number of elements and nodes in the finite element model.

Configuration setting	Elements		Nodes	
	Short root	Normal root	Short root	Normal root
C1	308,017	315,352	170,940	174,814
C2	302,344	309,511	167,846	171,568
C3	303,842	311,285	169,665	172,604

a clear trend of mesial and downward movement. The root experienced both the highest stress and the lowest hydrostatic pressure. Across all conditions, the first molar exhibited a distal torsion pattern, with the weakest distal torsion effect observed in C2 (Figs. 7,8).

For the second molar, stress concentration was also located at the cervical region in both short-root and normal-root groups. Under C1, the crown showed the greatest displacement in the X- and Z-axis directions, demonstrating a pattern of mesial buccal inclination and distal torsion. The tendency for downward movement was also most pronounced in C1. The maximum von Mises stress on the root and the minimum hydrostatic pressure were observed. In most of the conditions, buccal inclination of the crown was observed, except in the short-root group under C2 (Figs. 9,10).

4. Discussion

This study utilized 3D FEA to investigate orthodontic biomechanics in short-root anomaly (SRA) patients. It evaluated initial displacement trends and stress distributions *in vitro*. Studies demonstrated that FEA was a reliable method for such investigations [28]. To our knowledge, this is the first study

to assess stress distribution in the maxillary dentition during retraction with clear aligners in bimaxillary protrusion patients.

Results showed that the maxillary central incisors consistently tended to tip under all loading working conditions. Orthodontics relies on the centers of rotation and resistance to guide tooth movement. A recent study reported that, in a pulp cavity model, the average location of the center of resistance (Cres) was $58.8\% \pm 3.0\%$ from the root apex [29]. In clear aligner therapy, the Cres is closer to the apex than in fixed appliance therapy. This makes teeth more susceptible to tipping. Previous studies have also described a “roller-coaster” effect—characterized by extrusion and tipping—during anterior retraction with clear aligners [30]. Under C1, the normal-root and short-root groups showed the greatest movement and extrusion of the central incisor. The short-root group showed more pronounced extrusion, indicating greater tipping during clear aligner therapy. This finding aligns with Liu’s study [31]. To mitigate the roller-coaster effect in clear aligner therapy, recent studies have proposed increasing the gaps between the front teeth on torque and intrusion control of the central incisors for anterior retraction with clear aligners [32]. Other research has investigated the role of power ridge height in torque control [27]. However, the applicability of these methods to SRA patients still requires further investigation.

Anchorage control is another critical factor in orthodontic treatment. In this study, the mesial displacement of the anchorage teeth was most significant under C1. Enhancing anchorage in such cases poses a clinical challenge. In clear aligner therapy, anchorage reinforcement typically involves intermaxillary elastics [33], stepwise movement, and the use of miniscrews. However, in SRA patients, Class II elastics increased the force loaded on short-rooted anterior teeth. Whether Class II elastics is suitable for SRA patient still needs exploration. Our findings indicated that the stress on the central incisors in the short-root group was higher under C2 than under C1, suggesting that stepwise movement may not be the most appropriate strategy for SRA cases. Miniscrews, by contrast, provide stable anchorage, potentially leading to more controlled and predictable tooth movements [34]. Therefore, the combined use of aligners and miniscrews appears to be a promising approach for SRA patients’ tooth movements.

The orthodontic management of short-rooted teeth remains controversial. Much research have reported that short-rooted teeth are more susceptible to root resorption following orthodontic treatment [35], while orthodontic movement of teeth

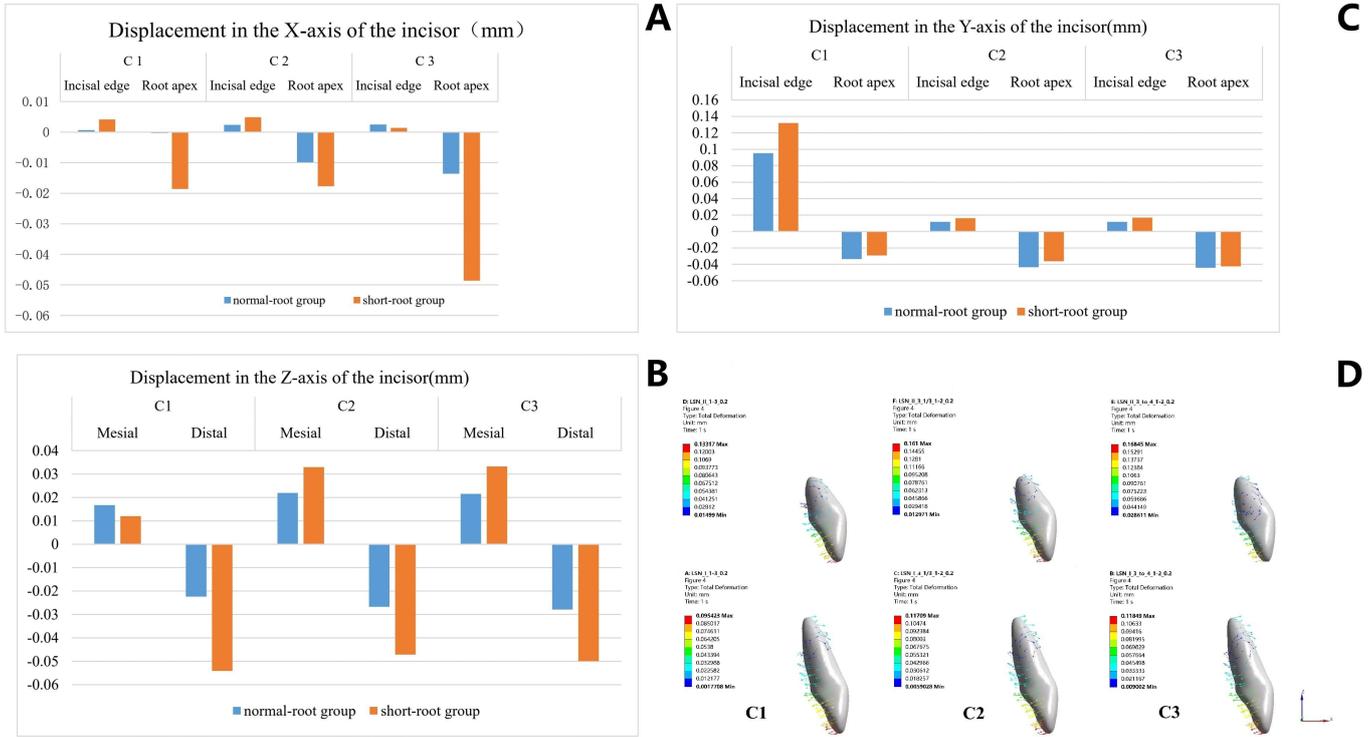


FIGURE 3. Movement of the upper central incisor. (A) The displacement along the X-axis was maximum in C3. (B) The displacement along the Z-axis was minimal in C1. (C) The greatest retraction occurred along the Y-axis under C1. (D) Histograms showing the 3D displacement (in mm) of the central incisor along the X-, Y-, and Z-axes under each movement condition. Max: maximum; Min: minimum.

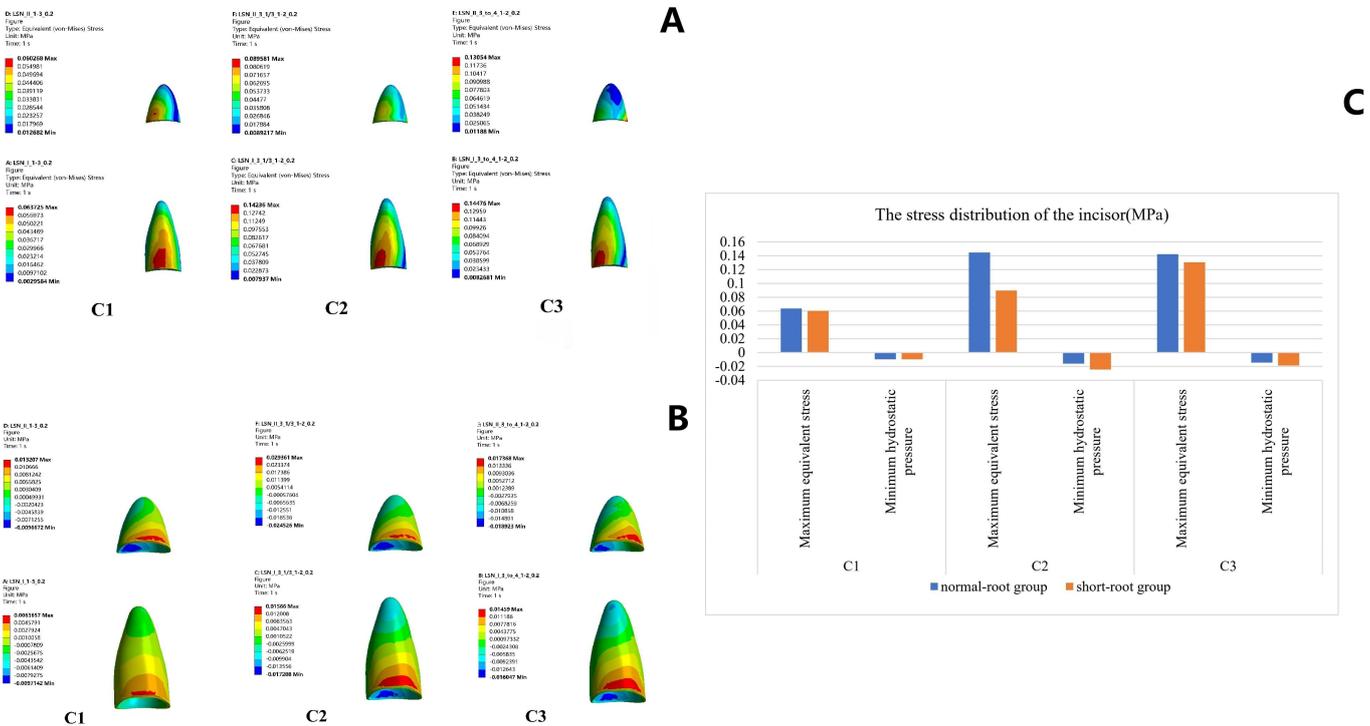


FIGURE 4. Stress distribution of the central incisor. (A) The largest von Mises stress was observed in the central incisor cervical area. (B) The minimum hydrostatic pressure was detected in the lingual cervical area. (C) The lowest stress distribution of the central incisor occurred in C1, the highest stress in C2. There was no significant difference in stress between the two groups under C1. Max: maximum; Min: minimum.

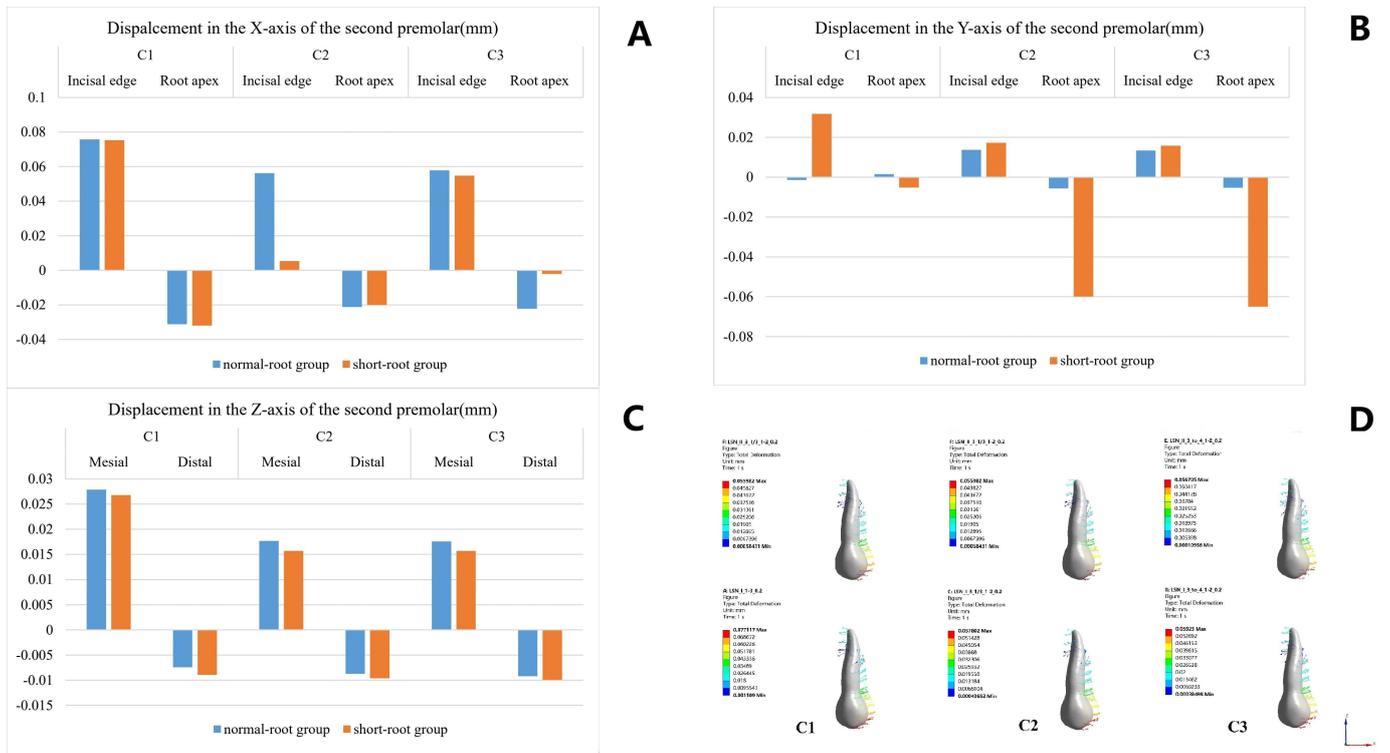


FIGURE 5. Movement of the second premolar. (A,C) The greatest displacement occurred along the X-axis and Z-axis under C1. (B) In the normal-root group, a slight buccal inclination of the crown was observed along the Y-axis in C1, whereas in other conditions the crown inclined lingually. In contrast, the short-root group exhibited the greatest lingual inclination of the crown under C1. (D) Histograms showed the 3D displacement of the second premolar. The short-root group exhibited less displacement compared to the normal-root group. Max: maximum; Min: minimum.

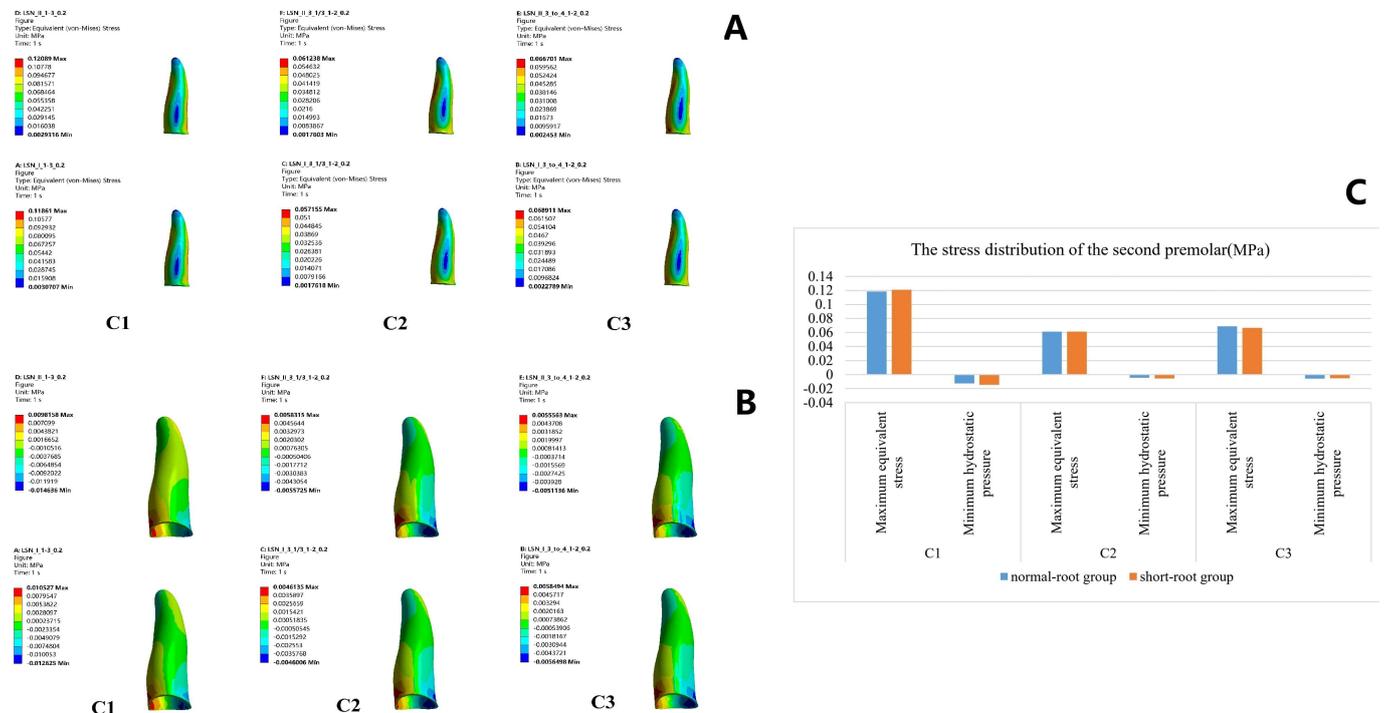


FIGURE 6. Stress distribution of the second premolar. (A) The largest von Mises stress of the second premolar was identified in the mesial root area. (B) The minimum hydrostatic pressure was detected in the mesial cervical area. (C) The highest stress distribution of the central incisor occurred in C1, while the lowest stress occurred in C2. Max: maximum; Min: minimum.

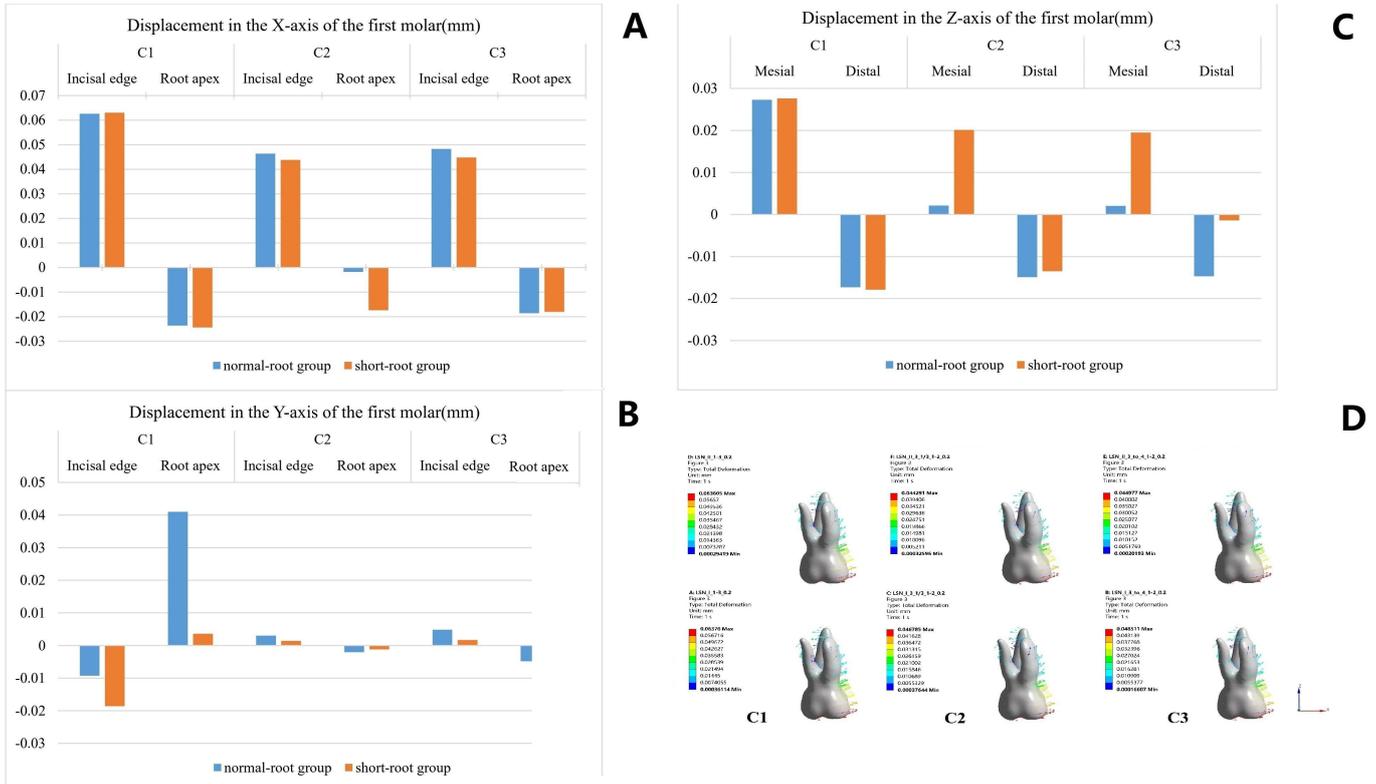


FIGURE 7. Movement of the first molar. (A,C) The first molar displayed mainly along the X-axis and Z-axis. The greatest displacement was observed near the mesial crown in C1. (B) Under C1, the greatest movement was on the root along the Y-axis. (D) Histograms showed the 3D displacement of the first molar. Max: maximum; Min: minimum.

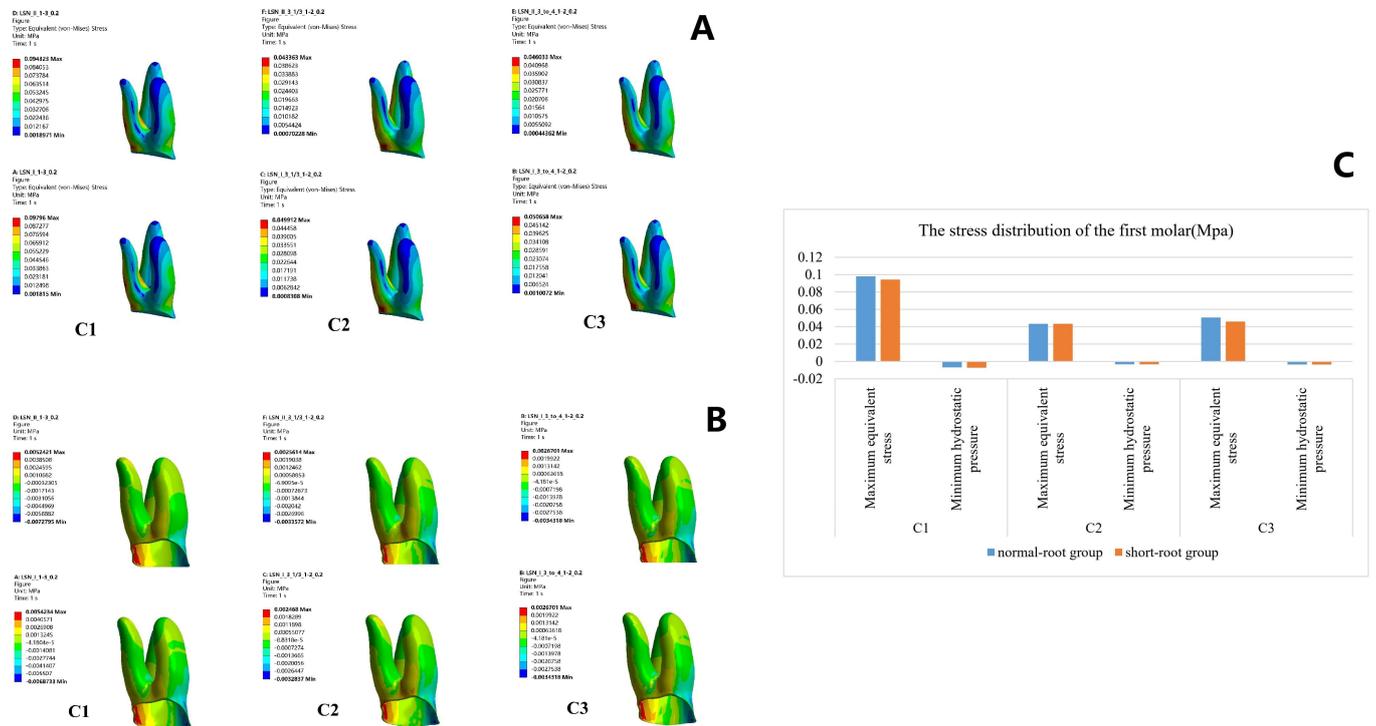


FIGURE 8. Stress distribution of the first molar. (A) The largest von Mises stress of the first molar was observed in the distal root area. (B) The minimum hydrostatic pressure was detected in the mesial cervical area. (C) The highest stress distribution of the first molar was observed in C1, and the lowest was in C2. Max: maximum; Min: minimum.

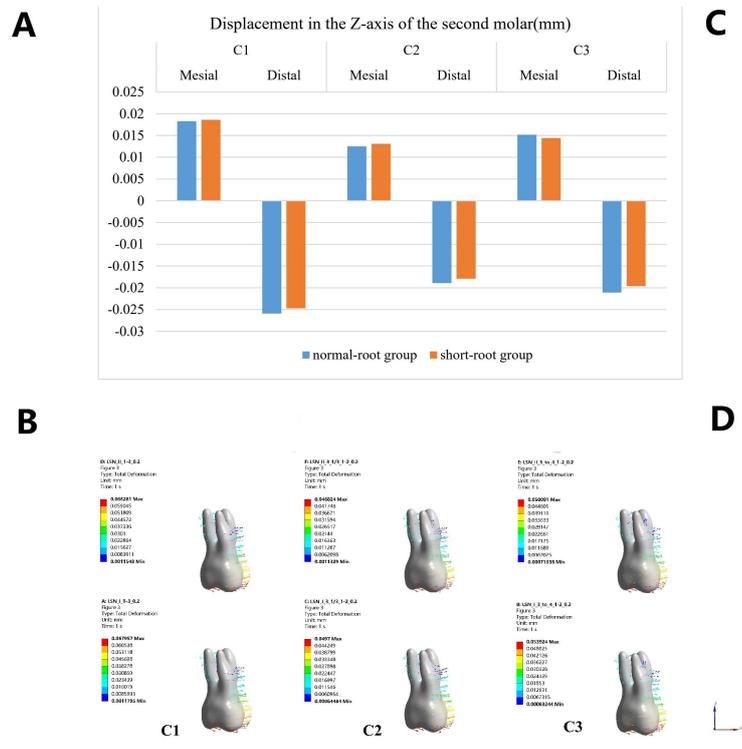
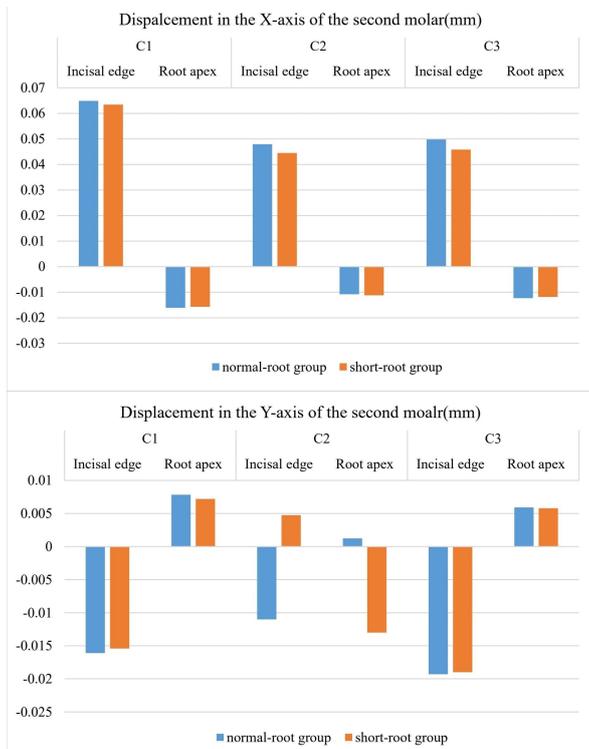


FIGURE 9. Movement of the second molar. (A,C) The greatest displacement occurred along the X-axis and Z-axis under C1. (B) Along the Y-axis, it demonstrated a pattern of buccal inclination. (D) Histograms showed the 3D displacement of the second molar. Max: maximum; Min: minimum.

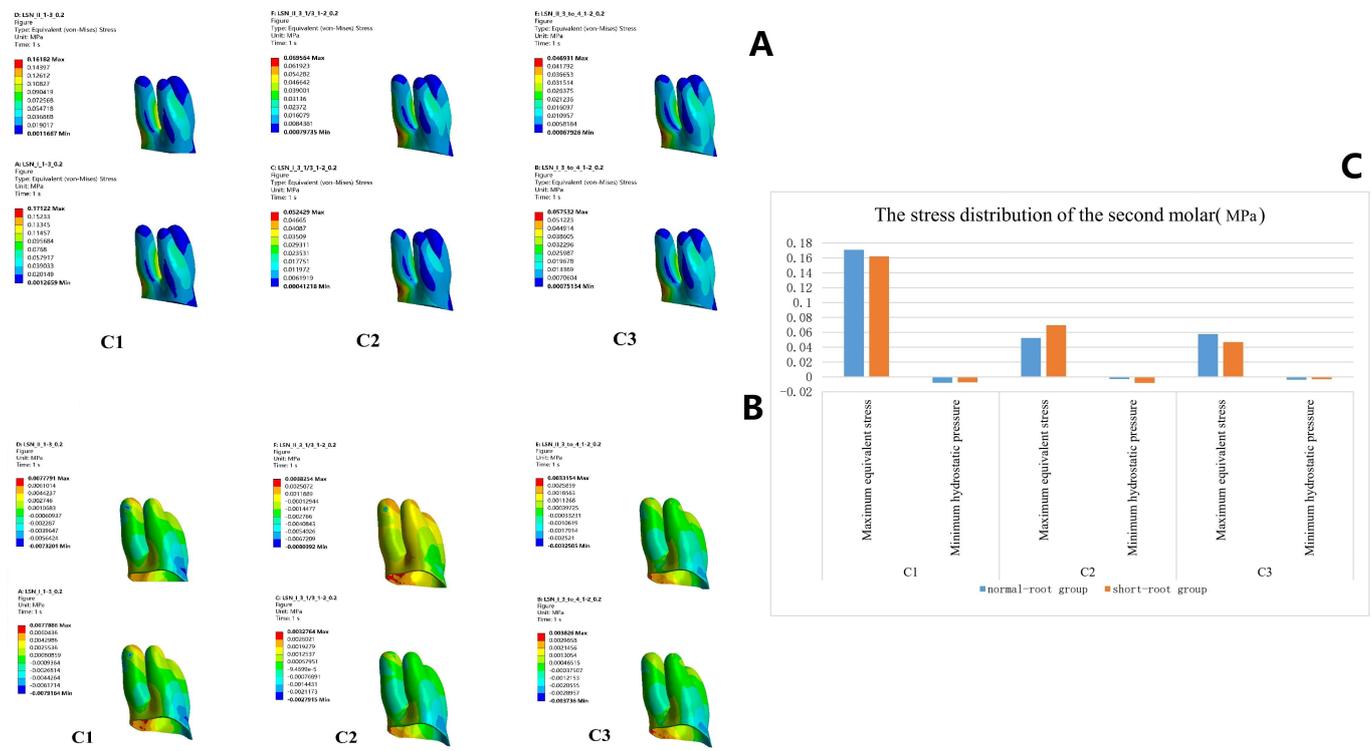


FIGURE 10. Stress distribution of the second molar. (A) The largest von Mises stress of the second molar was identified in the distal root area. (B) The minimum hydrostatic pressure was detected in the mesial cervical area. (C) The highest stress distribution of the first molar was observed in C1, while the lowest stress occurred in C2. Max: maximum; Min: minimum.

with SRA is only contraindicated in extreme cases. Caution at all stages could minimize attachment loss and lead to long-term stability [20]. Stress concentration at the root apex is a key contributing factor. In this study, however, root stress was predominantly concentrated in the cervical region, which may be attributed to the primarily tipping movement generated by clear aligners. We also observed that the minimum hydrostatic pressure of all periodontal ligaments exceeded 0.0047 MPa [35], potentially due to the relatively higher instantaneous forces exerted by clear aligners. In contrast, Zhang *et al.* [23] demonstrated that under the action of the lingual thin wire arch force system, the periodontal hydrostatic pressure of the maxillary central and lateral incisors remained below capillary pressure. Based on Rygh's principle of root resorption, it was speculated that such a force system root increases the risk of resorption [24]. Future finite element studies should include direct comparisons of stress levels under identical loading conditions for both fixed orthodontic treatments to optimize treatment planning. While Ke's study demonstrated that clear aligners offer advantages in facilitating segmented tooth movement and reducing overall treatment duration. However, they were found to be less effective than fixed appliances in achieving adequate occlusal contacts, controlling tooth torque, and ensuring long-term retention [36]. In premolar extraction cases, fixed appliances have shown superiority in establishing proper buccolingual inclination and occlusal contacts, often within a shorter treatment timeframe. Clear aligner therapy, on the other hand, provides more predictable and pre-programmed tooth movements. Both treatment modalities have been reported as effective in managing premolar extraction-based cases [37]. Healthy periodontal is important for SRA patients. Crego-Ruiz *et al.* [38] reported that clear aligners seemed to slightly maintain better periodontal health indices compared to fixed appliances.

Some clinicians' research [39] suggested that staging in Clear aligner plays a crucial role in achieving treatment success, and vertical rectangular attachments on canines are beneficial for achieving more predictable incisor tooth movements over optimized canine attachments [40]. In our study, SRA patients experienced the minimum stress on the central incisors under C1. Therefore, in this model, C1 appears to be a suitable movement for SRA patients.

The long-term stability of orthodontic treatment for SRA patients is quite important. Proper overbite, overjet and ideal torque control were the key factors for the stability. Early research mentioned that torque of the maxillary incisors was particularly critical in establishing a solid Class I relationship [41]. Several studies have reported an increased crown-root ratio in the anterior region and an increased incidence of abnormal crown-root morphology of anterior teeth in Class II division 2 patients [42]. Tang reported that the patients presenting with Class II division 2 malocclusion had a large crown-root ratio [43]. Another study found that oblique forces created greater stress which was not stable for the implants [44]. Another important factor for SRA of orthodontic prognosis is periodontal stability. There is a consensus that periodontal inflammation must be controlled before orthodontic tooth movement and must remain under control throughout the orthodontic treatment [45]. However, our study reflected an

“idealized” condition, which may differ in actual clinical use. It failed to provide a continuous simulation of tooth movement. Similarly, this research only reflected the initial displacement phase, so it could not fully replicate the complete orthodontic displacement process of short-rooted teeth. Another limitation of FEA is its inability to incorporate biological factors such as root length, root morphology, aligner material property, and bone density [27]. Additionally, the model used in this study was relatively based on a single patient's data, which limits generalizability, lacking attachments, power ridge or miniscrews. Future studies should aim to develop more comprehensive models, to dynamically simulate the full course of tooth movement and integrate more complex mechanical systems—such as intrusion, torque, varying bone densities and multi-vector forces—to further enhance clinical orthodontic guidance.

5. Conclusions

In summary, the short-rooted group exhibited greater root stress compared to the normal-rooted group in this study. For bimaxillary protrusion, overall retraction appears to be more suitable for SRA under the current conditions. Whether this retraction is appropriate in crowding malocclusion remains to be studied. Further experimental studies are needed to validate these findings. Moreover, the choice of anchorage support for short-rooted teeth may differ from normal-rooted teeth, suggesting the need for tailored orthodontic strategies. Proper overbite, overjet and ideal torque control after orthodontic treatment may be more important for SRA patients.

AVAILABILITY OF DATA AND MATERIALS

The data analyzed in this study are available upon request. Please write to the corresponding author.

AUTHOR CONTRIBUTIONS

SNL—conceived and designed the experiments, performed the experiments, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft. HS—analyzed the data, authored or reviewed drafts of the article, and approved the final draft. WYL, JYH, TZ, HMX and ZMD—analyzed the data, prepared figures and tables, authored or reviewed drafts of the article, and approved the final draft. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Informed consent was obtained from the patient and her parents, and the study was approved by the Ethics Committee of Nantong Stomatology Hospital, ethics number was PJ2023-029-01.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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